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MERCURY CADMIUM TELLURIDE SPUTTERED TARGET RESEARCH.(U)

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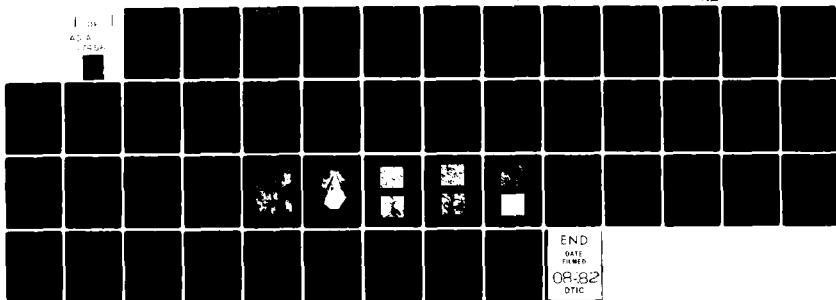
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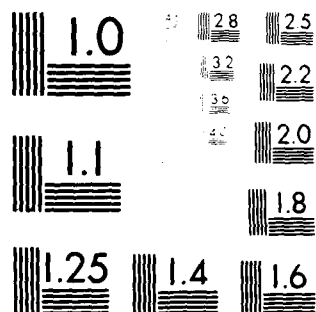
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Techniques for fabricating large-area targets by pressing either a local mixture of HgTe and CdTe powder particles (7 micron average size) or a similar-size powder ground from (Hg,Cd)Te polycrystalline ingots were developed. Sixty SEM microphotographs of regions of r.f. triode-sputtered targets, sputtered to different erosion depths, revealed topographical changes and dynamic erosion processes, e.g. cone formation and deterioration. The sputter-protect theory for cone formation due to larger, slow-sputtering particles (10-50 microns) was demonstrated. Distinctly different cone angle distribu-			

tions for HgTe and CdTe particles were measured; x-ray powder patterns revealed fusion of smaller HgTe and CdTe particles. To study compositional changes, six targets covered with silver-epoxied (Hg,Cd)Te,  $x=0.2$  ingots) were Hg-sputtered at 1, 1.25, and 1.6 mtorr for 1 to 5 minutes. Atomic concentrations of Hg, Cd, and Te were measured by ESCA as a function of depth and time using minus 77°C bromine-methanol back-etching of ingots. An initial decrease of Hg and Cd at the surface was observed; steady state surface concentrations depended on Hg pressure. Using the experimental data, a first-order model for compositional changes was developed. Computer calculations show that the altered layers changes from 0.32 microns after 5 minutes of sputtering at 1.6 mtorr to 1.2 microns after 65 minutes.

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## I. Foreward

This research was done as part of a continuing effort since 1975 by the NJIT Microelectronics Lab to develop sputtering technology for the deposition of large area, single crystal thin films of Mercury Cadmium Telluride,  $(\text{Hg}_{1-x}\text{Cd}_x)\text{Te}$ , with controllable value of  $x$ , onto CdTe and low-cost silicon substrates<sup>1,2</sup>. The application of these films is to high performance, low cost infrared detectors and detector arrays for response to radiation in the 3-5, 8-12 and 14-30 micron wavelength region. Research sponsored by the Air Force Office of Scientific Research, grant No. AFOSR 77-3249, concentrated on the study and optimization of the optical, structural, and electrical properties of rf triode-sputtered thin films. The purpose of the research reported in this document was to study the very complex physical and chemical processes associated with the removal of  $(\text{Hg,Cd})\text{Te}$  target material by bombardment of Hg ions, for deposition of thin films. In addition to obtaining results of scientific interest, the research solved many practical problems associated with the fabrication of large area, minimum cost sputtering target, with different  $x$  values.

The fabrication and use of many pressed-powder targets were required to deposit the large number of films required for study of deposition and annealing methods for optimizing the properties of sputtered  $(\text{Hg,Cd})\text{Te}$  films. Altogether about 80 target discs of  $(\text{Hg,Cd})\text{Te}$  were fabricated between 1977 and 1982 for film deposition purposes. These targets were almost all made by pressing powder mixtures obtained by grinding HgTe and CdTe polycrystalline ingots into relatively firm discs, 5.7 cm. diameter, epoxied onto five inch diameter backing plates.

The study of the effect of Hg ion bombardment of  $(\text{Hg,Cd})\text{Te}$  targets was divided into two phases. In the first phase (March 1978-June 1979), the research study concentrated on practical methods of fabricating low-cost targets and study of the topographical target surface changes due to ion bombardment, an area of research still in its infancy. The background for topographical surface changes induced by ion bombardment and the NJIT research results are reported in detail in a 263 page MSEE thesis by Thadeus Gabara<sup>3</sup>, which contains 60 SEM photographs and 53 references related to the science and technology of ion bombarded surfaces. The NJIT research concentrated on the physical changes in low-cost targets, made by pressing either powder ground from  $(\text{Hg,Cd})\text{Te}$  ingots or powder mixtures ground from relatively low-cost HgTe and CdTe ingots. These pressed-powder targets were used to make the studied  $(\text{Hg,Cd})\text{Te}$  thin films. The main results of this target research are reported in section II and will be written for publication in 1982. In phase two (June 1979-March 1981 and the no-cost extension period of March 81-May 82), the compositional changes occurring in  $(\text{Hg,Cd})\text{Te}$  targets were studied using controlled chemical back-etching and ESCA chemical surface analysis. The compositional change study was made using pieces of  $(\text{Hg,Cd})\text{Te}$ ,  $x=0.2$  ingots epoxied onto pressed-power



targets. The NJIT results and background for research in compositional changes of sputtered targets are given in detail in a recently published 157 page thesis<sup>4</sup> completed by Robert Bourne in May, 1982. The major experimental and computer calculated results will be written for publication in 1982 and are presented in section III. Section IV of this report discusses some of the practical information found in the target research. Section V states final conclusions and suggestions for future research in the science and technology of sputtered compound-semiconductor targets.

## II. Experimental Study of Topographical Changes in (Hg,Cd)Te Pressed-powder Targets

### A. Introduction:

It is well-reported in the literature<sup>5,6,7</sup>, that surfaces do not maintain their initial contours when bombarded by ions; cones, ridges, furrows, craters, hillocks etc. may appear as the surface is eroded away. In this research, the erosion of two types of (Hg,Cd)Te surfaces, that are used to sputter thin films, was experimentally studied in some detail. One of the target surfaces was that of pressed-powder particles from (Hg,Cd)Te ingots; the other surface was composed of a pressed-powder mixture of HgTe and CdTe particles. Knowledge of topographical changes of these surfaces when ion-bombarded is important for understanding and controlling the film deposition rate, the falling of particles onto the substrate of down-sputter production deposition systems, and the useful lifetime of targets. The application of this research is not only to the practical problems associated with (Hg,Cd)Te film deposition but also to ion milling of (Hg,Cd)Te material which should become an area of interest as the technology of (Hg,Cd)Te devices develops.

The collision processes involved in the impact of ions on target surfaces and the known theories for cone formation are reviewed in chapters II and III of Mr. Gabara's MSEE thesis.<sup>3</sup> Also included in this thesis are details on the preparation, mounting, installation and ion bombardment of the target discs used in this research. The thesis contains over 50 SEM (1000 times magnification) of the two target surfaces experimentally studied. The most important findings of this experimental study will be summarized in section II-B of this report.

### B. Experimental Results and Conclusions

The erosion processes of the two types of pressed-powder targets were studied by sputtering the targets under typical film deposition conditions. The deposition parameters were: average rf power density across the target surface, 20 watts/cm<sup>2</sup>; Hg sputtering gas pressure, 1 micron; sputtering time, 6 hours; target rf voltage, about 2000 volts. The solid solution target (S.S. target) was composed of pressed-powder particles from (Hg<sub>75</sub>Cd<sub>25</sub>)Te ingots, with a particle size distribution in the 3 to 50 micron range (average size 7  $\mu$ m). The thickness and diameter of the disc were 0.154 and 2.86 cm. respectively. A target density of 6.52 g/cm<sup>3</sup> (87% of the density of 7.5 g/cm<sup>3</sup> for a single crystal of x = 0.25 material) was obtained with an 80 ton press applying  $2.63 \times 10^8$  newtons/m<sup>2</sup> pressure

for several hours. The physical mixture target (PM target) was made from a homogenized mixture of HgTe and CdTe particles pressed to a density of  $7.14 \text{ g/cm}^3$  with  $2.66 \times 10^8 \text{ n/m}^2$  pressure. The average sizes of the HgTe and CdTe particles were 9 and 7.3 microns respectively. The percent molar concentration of the CdTe particles (the effective target x values) was 0.25. The target disc had a diameter of 2.86 cm. and a thickness of 0.05 cm. The P.M. and S.S. targets were epoxied onto the center of 12.7 cm. diameter, stainless steel backing plates, containing a recess of about 2 mm., as shown in figure 1. Figure 2 shows the position of the mounted target in the target assembly. Figure 3 is a schematic drawing showing the position of the target assembly in the modified MRC 8800 triode-triode-sputtering system used for film deposition.

The stainless steel mask in front of the 2.86 cm. diameter target discs, to prevent sputtering of the stainless steel backing plates, served to focus the ions near the mask edge so that the ion dosage and erosion rate varied across the target. Figure 4 shows that the maximum erosion rate  $175 \text{ \AA/sec.}$ , occurred about 0.9 cm. from the center of the target disc, while the outer rim of the disc contained unsputtered and very lightly sputtered regions (regions A and AB). Thus from the "erosion profile" of the target, it could be divided up into nine regions, A-I on the top of figure 1, each having different incident ion dosage, different erosion rates, and different topography.

To give the reader some idea of the striking topographical changes that were observed in this research, xeroxed copies of a few of the 60 SEM microphotographs taken at Structure Probe Inc., Metuchen, N.J. are shown in figures 5-9. The microphotographs froze the dynamic changes in erosion (including complex cone formation and deterioration processes) at a time when the central portion of the target had been eroded to a depth of 250 microns. Figure 5 shows large perfectly shaped cones on the left and partially deteriorated cones on the right in a highly eroded region F of the SS target. Formation of many smaller cones can also be observed. From photographs such as in figure 6, tiny submicron steps on the sides of cones can be observed. Figures 7 and 8 show the formation of cones on the sides of large ground particles in the PM target. Figure 7a shows one of the few impurities observed on the target surface and its cone-like shape. Figure 5-9 shows unsputtered regions of the PM target from which initial particle size distributions can be found.

The following lists the main conclusions that can be drawn with respect to topographical changes in pressed-powder (Hg,Cd)Te targets due to Hg ion bombardment. The conclusions are based on the microphotographs as well as on results obtained with energy dispersive electron probe microanalysis (EDX) attachment to the Structure Probe SEM.

1. The most striking characteristic of the sputtered surfaces of both PM and SS targets is the formation and erosion of cones. The xeroxed photographs in figures 5-8 illustrate some of the observed surface features including perfectly shaped cones, fractured cones, and complex cone formation. Cones as high as  $150 \text{ }\mu\text{m}$  were observed. The vertex angle and height of the largest cones found in different regions

of the S.S. target are shown in figure 4. Cones were observed to form under large particles with relatively lower sputtering rates. The sputter-protect theory (8) for cone formation, with protection due to impurities, was supported by our results, where the protecting layer on the tip was not an impurity but a large particle sputtering more slowly due to either its particular orientation or composition. Smaller particles erode much faster because they have a total combined perimeter exceeding that of large particles and therefore an increase in exposed surface area with a slope  $\hat{\theta}$ , where  $\hat{\theta}$  is the surface angle for maximum sputtering yield.

The formation of large cones should be avoided by removing particles greater than 10 microns from the powder pressed into a target. The smallest aperture sieve that NJIT was able to purchase passes particles as large as 45 microns. An effective method to remove particles greater than 10 microns without contaminating material has to be found. The disadvantage of cones are that they can break and fall down onto the substrate. Also the emission of sputtered material is not as directional when the target has angled surfaces. Finally, for the same applied target power, the film deposition rate will be higher if the target is composed of smaller, faster eroding, particles only.

2. Despite the drastic changes in the surface topography and the formation of altered surface compositional layers, the deposited film composition did not appear to change over at least 12 hours of sputtering time of PM and S.S. targets. This is probably due to the averaging of the emission of many different particles in the sputtering target. The large number of cones did cause the emission of material at more oblique angles than one would expect.

3. The behavior of the cones followed the theory of Stewart et. al (5). The large angled slope of each particle eroded toward the center of the particles. Once cones formed, they sputtered at a faster rate than flat surfaces because the sputtering yield is a function of the angle of incidence of the bombarding ions. "Steady-State" cone angles corresponding to the angle for maximum sputtering yield were obtained. Craters were observed to form at the base of cones in support of the reflected ion theory of Barber.<sup>6</sup>

4. In the PM target distinctly different cone angle distributions were observed for cones with HgTe and CdTe particles on their peaks. Smaller angles cones had HgTe peaks, as expected since the sputtering rate of HgTe is greater than CdTe. The cone angle distribution for the S.S. target was in between those for CdTe and HgTe cones.

5. In the highly eroded groove near the outside of the target (caused by ions deflected away from the shield), sputtered material from the sides of the groove redeposited on the cone tips and appeared to slow their erosion rate.

6. An interesting feature of the cone deterioration in the S.S. target was the formation of submicron sized steps on the cone walls. The steps appeared to form at the cone tip, due to the sudden complete erosion of a sputter protect particle, and to propagate down the sides, slowing up when encountering slow-sputtering particles.

7. Spongelike objects, that appeared to be fractured cones that perhaps had Hg or HgTe boiled off them, were observed in a few target locations. The composition of the objects could not be determined due to their small size.

8. The question of whether HgTe and CdTe particles in an ion bombarded PM target diffuse into each other to form (Hg,Cd)Te material remains unclear. On the one hand, the electron microprobe (EDX) scan showed that the tops of cones of the studied PM target had distinctly different angles for HgTe and CdTe cones. However, the x-ray diffraction powder pattern of a powder ground from a sputtered target indicated that there was a single phase of (Hg,Cd)Te and not a mixture of HgTe and CdTe, indicating that annealing of the PM target causes homogenization. Also, one cone that had accidentally fractured appeared to have a shell of solid (without particles) material about 0.8 microns thick on the surface of the cone. However, when cones were deliberately fractured and then examined by SEM, no solidified regions were observed on the inside of the cones. The author believes that interdiffusion of the smaller HgTe and CdTe particles probably occurs when the target is sputtered and that the extent of annealing depends on sputtering conditions, particularly the surface temperature of the target.

### III. Experimental Study of Compositional Changes in (Hg,Cd)Te Targets.

#### A. Introduction

A major objective of this research was to study the compositional changes in Hg-bombarded target material. When a multiconstituent material is sputtered, the surface of the material will undergo compositional alteration in a region known as the altered layer. Prior to sputtering there is, of course, no compositional variation between the surface and the bulk. As the target surface begins to be eroded away by the impinging ions, the elements will be removed at different rates dependent upon their sputtering yields. The yields of the different constituents are not related in any simple manner to the individual elemental sputtering yields. In multiconstituent material, the different sputtering yields are influenced by factors such as binding energy and atomic mass. The result is a target whose elements sputter at different rates, causing a compositional variation between the surface and the bulk. Compositional gradients cause the migration of elements to the surface. Defects, vacancies, and interstitials caused by sputtering collisions can enhance the motion of the diffusing species. The sputtering yield gradients will continue until a steady state is obtained. At this point the rate of elements diffusing from the bulk to the surface will equal the rate at which the elements are being sputtered away. The altered layer shows a compositional variation between the surface and the bulk due to the elements' assorted sputtering yields and diffusion coefficients.

The purpose of studying changes in composition versus depth into the target was to obtain a better understanding of the complex sputtering phenomena that make it possible to obtain thin films of (Hg,Cd)Te by sputtering. Alterations produced on the surface of a sputtering target

due to ion bombardment will be reflected in the composition of the thin film. Knowledge of a compound's altered layer structure is of practical benefit when working with sputtered thin films and ion beam etching. In particular, it is very useful to know how long it takes for the surface to reach an equilibrium value when it is bombarded under sputtering conditions. If the target is bombarded for this amount of time while the thin film substrates are shielded to prevent growth, then it is possible to avoid deposition of material with varying composition. This pre-sputtering process is used to obtain the equilibrium composition and clean the target surface.

One problem that was immediately encountered in our research was that almost all surface analysis techniques (9) were not suitable for measuring the altered layer composition of (Hg,Cd)Te. ISS, SIMS and IPM (Ion Scattering and Secondary Ion Mass Spectroscopy and Ion Probe Microanalysis) all involve sputtering to remove material. Electron Probe Microanalysis, Spark Source Mass Spectrography, and x-ray Fluorescence Spectroscopy all have sampling depths of at least 100 atomic layers, making them unsuitable for depth profiling of the altered layer. It was found by measurements at Structure Probe Inc., Metuchen, N.J. that the energy density of the incident electron probe (with a diameter of one micron) were too high to leave the (HgCd)Te composition unchanged when sensing the composition. Only ESCA, Electron Spectroscopy for Chemical Analysis, and its x-ray counterpart XPS (x-ray-induced Photoelectron Spectroscopy) was found to be suitable for sensing the elements in a 2-10 atomic layer thickness without changing the composition. In the XPS system used, the sample is bombarded by x-rays spread over a 1 cm. square area and the energy of the emitted electron is related to the binding energy of the electrons, which is unique to each type of atom. The particular instrument used at Structure Probe Inc., Metuchen, N.J. was a Perkin Elmer Model 549 which used a Mg source to irradiate the (Hg,Cd)Te samples in a  $10^{-9}$ - $10^{-10}$  torr vacuum with 1253.6eV x-rays.

The wide beam characteristic of XPS made it impossible to use for analysis of pressed-powder targets, which have particles with sizes in the 3-50  $\mu$ m. range. Therefore it was necessary to use expensive targets with (Hg,Cd)Te ingots. Fortunately, about 50 (Hg<sub>0.8</sub>Cd<sub>0.2</sub>)Te rectangular ingot sections (1 x 3 x 0.7 cm.  $\pm$  20%) were given to NJIT by Peter R. Bratt of the Santa Barbara Research Center. The total area of these flat ingot pieces was sufficient to obtain six sets of composition versus depth data. A new type of target was designed having six to eight ingot pieces silver-epoxied to pressed-powder, x = 0.2 targets. The area of the pieces with uniform ion bombardment was back-etched to different depths to obtain composition versus depth. Thus a fundamental study of ion-bombarded (Hg,Cd)Te material was made whose results can possibly be extrapolated to HgTe and CdTe targets and to pressed-powder targets consisting of either many HgTe and CdTe particles sputtering in parallel or to (Hg,Cd)Te particles obtained by interdiffusion of HgTe and CdTe.

Besides surface analysis, two other serious difficulties were encountered in the composition study. The controlled back-etching of (Hg,Cd)Te material proved to be a more difficult task than expected; many experiments had to be conducted over a 4 to 5 month period before

a low temperature etching procedure for removal of  $100 \text{ \AA}$  to  $250 \text{ \AA}$  of material from the surfaces of the ingot pieces could be done in a well-controlled manner. Another difficulty was that although it was desirable to obtain data on changes of composition as a function of Hg sputtering gas pressure, target x value, sputtering rate and incident rf power, depth of position into the target, and sputtering time, only six sputtering runs could be made due to the cost and time involved in the sputtering runs and ESCA measurements and the limited amount of suitable target material available. Therefore, an effort was made to use the limited experimental data to develop a computer model which could be used to predict compositional changes in the target as a function of the parameters listed above.

#### B. Chemical Back-Etching

The required etch rate to remove material in  $100 \text{ \AA}$  steps is in the 5-15  $\text{\AA}/\text{sec}$  range. Initial experiments showed that the etch rate for the "standard (Hg,Cd)Te etch" of 1% (by volume) of Bromine Methanol was in the 200-1000  $\text{\AA}/\text{sec}$ . range for only 20 sec. of etching. It therefore was found necessary to develop a well-controlled etch procedure by lowering the etch temperature. In the final procedure developed, the etched sample was kept at  $-78^\circ\text{C}$  in a vertical position in a beaker filled with dry ice and acetone. Acetone was added to the dry ice to attain constant temperature, since it has a lower melting point. A magnetic mixing machine was used with an apiezon-coated stirring magnet. Apiezon "black wax" was used to cover a portion of the etched ingot piece so that an etched step would be obtained, which was measured by SEM. The apiezon was removed in a 6 step procedure consisting of three 40 minute baths of trichloroethylene, one of methanol to remove any  $\text{HgBr}_2$ , one of isopropanol, to dissolve any  $\text{TeBr}_2$ ,  $\text{TeBr}_4$ , or  $\text{CdBr}_2$ , and a final warm  $\text{H}_2\text{O}$  bath. When the apiezon is used at  $-78^\circ\text{C}$ , the sample has to be slowly warmed back to room temperature or the wax will flake off with (Hg,Cd)Te material.

Figure 10 shows data obtained during the etching research study. Note first that the incremental etch rate decreases with time. Also note the surprising result that the etch rate for the ingot pieces laid horizontally is very slow, but much less controllable. This is probably due to etched material laying on the surface and protecting it from contact with fresh etchant. The data in figure 10 obey the equation

$$\text{depth} = A \exp(B/t)$$

where  $t$  is the etch time in seconds and  $A$  and  $B$  are constants which were obtained by curve fitting. The  $A$  and  $B$  values are: for run D42,  $A = 34,800 \text{ \AA}$  and  $B = 23.81 \text{ sec.}$ ; for run D43,  $A = 157,100 \text{ \AA}$  and  $B = 21.56 \text{ sec.}$ ; for run D48,  $A = 95,680 \text{ \AA}$  and  $B = 26.44 \text{ sec.}$  To obtain an even lower etch rate than that shown in the figure, the Bromine concentration was reduced further. Etch depth data for reduced concentrations at  $-78^\circ\text{C}$  are shown in the following table.

Etch Time [sec.]	Br <sub>2</sub> Conc [%]	Depth [Å]
10	0.001	113
20	0.001	263
10	0.01	245
20	0.01	396
10	0.1	2517
20	0.1	3846

### C. Sputtering Procedure

Due to time and cost limitations, only seven sputtering runs with targets having epoxied ingots could be made. This limited the sputtering deposition parameters that could be experimentally studied. Since it was particularly desirable to find how long it takes for the surface composition and altered layer to reach an equilibrium condition and since time would be a key variable in any mathematical model to calculate sputtered target composition versus depth, total sputtering time was one key variable that was changed. Applied rf power, upon which deposition rate and erosion rate are known to have a linear dependence, was kept constant at 200 watts. Some variation of target voltage occurred during the runs (1600-2000 volts) but this variation is thought to have little effect on the results. The other important parameter that was varied was the pressure of the Hg vapor, which is known to have an effect on film properties and therefore should effect target compositional phenomena. The sputtering time and Hg vapor values used for the six targets sputtered are given in columns 4 and 5 in figure 11a. A seventh run was made with one micron Hg pressure and a sputtering time of 2 minutes but unfortunately the run was aborted. Complete information for a typical run, disc 80, is shown in figure 12.

### D. Experimental Results

Figure 11b shows typical ESCA data obtained using the Perkin Elmer Model 549 at Structure Probe Inc. Large concentrations of oxygen, nitrogen and carbon, which are always present in elemental or compound form on the outer atomic layer of any material, were also detected by the ESCA measurements. These concentrations can be neglected with respect to the composition of the first ten atomic layers of the "surface measurement"; therefore the Hg, Cd and Te concentrations, the three columns the right, are normalized to 100%. That is, it is assumed that any impurity has a concentration much less than that for Hg, Cd and Te. Figure 11b gives the adjusted, normalized values of Hg, Cd and Te for ingot pieces with different etched depths for the six runs. The data were adjusted using a standard piece of (Hg,Cd)Te, with known x-value. Note that the dates of the backetching and ESCA measurements are given in column 3 and that the ingot pieces from discs D79 and D67 were etched twice to obtain the composition profile at a greater depth. These compositional data for Hg, Cd and Te are plotted in figures 13-18 and compare with data calculated using the altered layer model.

### E. Altered Layer Computer Model

Two computer models were investigated for predicting the compositional changes in ion-bombarded (Hg,Cd)Te targets. The first, called surface, was developed by NJIT graduate student Robert Bourne as an extension of a simple model conceived by Paterson and Shirn<sup>10</sup> in 1967 to describe the altered layer formation in the binary alloy NiCr. This model assumes an infinitesimally thin layer being sputter-etched on one side and having the sputtered elements replenished by diffusion from the bulk. Shirn did not correlate the results of the model with experimental data and neglected interstitials and vacancies. The surface model was extended to 3 elements by Bourne.<sup>4</sup> It will not be discussed further since it can only predict surface concentration and is based on limiting assumptions. A more promising model was developed at NJIT to predict composition versus depth. This mathematical model, called Altered Layer, was based on work by Jost for the general field of diffusion.<sup>11</sup> As far as this author knows, it has not been applied to sputtering. Jost solved the diffusion equation between a layer of finite, fixed thickness and an infinitely thick bulk region. Bourne modified Jost's equation to account for diffusion from the target bulk region, which is assumed infinitely thick, as well as diffusion of Hg from the front surface of the target. Both the composition and thickness of the altered layer region will change with time and will be a function of the concentration of Hg diffusing into the front surface due to the Hg ion bombardment, the rate of sputter-removal of Hg,Cd and Te atoms from the front surface and the rate of diffusion of the elements from the bulk region into the altered layer. The result will depend on the x value, the % composition of Cd, of the target material. It was also assumed that the concentration of Hg at the surface was linearly dependent on Hg pressure. It is also expected that the influx of Hg will be proportional to the number of vacancies created by sputtering and therefore proportional to the applied target power and etch rate. [Experiments changing applied target power have not yet been done].

The Altered Layer model is based on the set of equations:

$$(1) C_i = \left[ \frac{C_{si} - C_{bi}}{2} \right] \cdot [\operatorname{erf} a - \operatorname{erf} b] + C_{bi}$$

$$\text{Where } a = \frac{h+x}{2\sqrt{D_i t}} ; b = \frac{h-x}{2\sqrt{D_i t}} ; \operatorname{erf} a = \int_0^a e^{-z^2} dz$$

and

$C_i$  = concentration at some position x in the altered layer of one of the 3 elements in atoms/unit area; i = 1, 2, 3.

$C_{si}$  = surface concentration of one of the 3 elements in atoms/unit area.

$C_{bi}$  = bulk concentration of one of the 3 elements in atoms/unit area.



$h$  = finite thickness of altered layer; fixed in Jost's work, changing with time in Bourne's model.

$t$  = time [sec]

$D_1$  = diffusion coefficient [ $\text{\AA}^2/\text{sec}$ ]

To account for the variation of  $h$  with time the following equation was written (as suggested in Jost's work) where the  $K$ 's are constant values, independent of time and Hg pressure, for each element found from the experimental data by curve fitting.

$$(2) \quad h = 2K_i\sqrt{D_1t} \quad \therefore a = K_i + \frac{x}{2\sqrt{D_1t}} \quad \text{and} \quad b = K_i - \frac{x}{2\sqrt{D_1t}}$$

The diffusion constants chosen by curve fitting the 3 min., 1  $\mu\text{m}$  run data were  $K_{\text{Hg}} = 7.6$ ,  $K_{\text{Cd}} = 2.2$  and  $K_{\text{Te}} = 4.3$ . These values were then used to obtain the diffusion coefficients by a lengthy trial and error, best fit technique to the 1, 1.25, and 1.6  $\mu\text{m}$  data; the diffusion coefficients used to compute the curves in figures 13-18 are reasonable values and are given in the table below. Note that the coefficients decrease somewhat with the influx of Hg from the surface (Hg pressure).

Diffusion Coefficients ( $\text{\AA}^2/\text{sec}$ )

Hg Pressure ( $\mu\text{m}$ )	Hg	Cd	Te
1.0	$25 \times 10^3$	$25 \times 10^3$	$66 \times 10^3$
1.25	$17 \times 10^3$	$17 \times 10^3$	$50 \times 10^3$
1.6	$8 \times 10^3$	$16.6 \times 10^3$	$21 \times 10^3$

To implement the equations of the model on a computer without integrating capabilities, the error function was approximated by the summation of 100 slices.

$$(3) \quad \text{erf } a = \int_0^\infty e^{-z^2} dz = \sum_{z=0}^a \exp(-z^2) \cdot \frac{a}{100}$$

The Altered Layer model written in BASIC language is given in figure 19.

#### F. Discussion of Experimental and Model Results

From the ESCA data for Te, Cd and Hg percent atomic concentrations, plotted in figures 13-16, it can be first observed that there is generally a depletion of Hg and Cd at the surface of the target and an enhancement of Te. Note that the percent concentrations of Te, Hg, and Cd in the bulk are 50, 40, and 10% respectively for  $x = 0.2$  material. Data from a relatively few etched samples are not in agreement with most of the other data and the computer model results. Particularly, the surface data shown in figure 13 appear to be erroneous since the data for the other runs did not show a sharp dip in Hg in the first 100  $\text{\AA}$ . The data of figures 13-16 also indicate that the surface concentration

reaches an equilibrium value in less than 5 minutes and probably in less than 3 minutes. The data for 1.6 micron Hg pressure runs, figures 17 and 18, show a somewhat different behavior; for the 5 minute run the Hg concentration is almost as high at the surface as it is in the bulk; it dips down at about 900 Å before rising to bulk value at the termination of the altered layer. [This dip in Hg also appears in computer calculated results for much longer periods of time, as shown in figure 20.] Most of the data for figure 18 are reasonable and follow the calculated data from the model; only the Cd data points at 1250 and 2750 Å appear to be in error. The experimental data for the 5 min., 1.25 micron run, figure 16, also agree particularly well with the model results. We note that both the Cd data and the calculated data reach bulk concentration values much more quickly than the Hg and Te data. Figure 17, which shows a plot for the 1 min., 1.6 μm run, has one set of clearly erroneous data, for 600 Å, and more deviation from the model results than the other runs. The data for the 3 min., 1 μm run, figure 15, for distances less than 1250 Å, are in fairly good agreement with the model results. This sample was etched twice to obtain data at depths greater than 1250 Å. The set of data for depths greater than 1250 Å, particularly the Cd data, was the only set of ESCA data completely unreasonable with both other experimental data and with the model results. The data shown in figures 13 and 14 reasonably follow the model results except for the 0 and 225 Å data of figure 13 and the 225 Å data of figure 14.

The following general conclusions regarding the formation and growth of the altered layer can be drawn from the experimental data:

1) The data of figures 17 and 18 show that there is an initial decrease of Hg and an increase in Cd when a target is sputtered with 1.6 mtorr of Hg. This could be related to the higher sputtering yield for Hg versus Cd and higher diffusion coefficient for Cd versus Hg. After one minute of sputtering, the surface concentrations have not reached equilibrium but are changing with time.

2) When the surface concentration reaches equilibrium, there is a depletion of both Hg and Cd at the surface of sputtered targets dependent on the Hg sputtering gas pressure, as shown in figures 15, 16, and 18. At 1.6 micron pressure after 5 min. of sputtering, figure 18, the Hg concentration is almost the same as the bulk value; however, this is done at the expense of Cd whose concentration is depleted to a value close to zero near the surface. [This result correlates with poor film results for Hg pressure greater than 1.5 μm for solid solution targets at NJIT and as reported by other researches (12)].

3) The altered layer thickness increases with time, as expected. The concentration measurements for the 1.6 micron, 5 min. run were taken for sufficient depth to be correlated with calculated data throughout the entire altered layer thickness of about 3200 Å. The other compositional data were not obtained for depths corresponding to the full altered layer depth, since it was estimated that the altered layer would be thinner than it was found to be. The motion of the edge of the altered layer into the bulk can be observed from the 1 mtorr Hg pressure data in figures 13 - 15. It is seen that the altered layer increases with time at a decreasing rate. Recent computer

analysis results for large sputtering times, as shown in figure 21, show this to be the case.

- 4) The Cd concentration reaches its bulk value in a shorter distance than the Hg and Te concentrations.
- 5) Comparing the 5 minute data for 1.6 and 1.25 mtorr Hg pressure, it appears that the altered layer is deeper when the sputtering gas pressure is less (under constant applied rf target power conditions); there is less of an influx of Hg at the surface to replenish sputtered atoms.

Although more experimental data would be very desirable, sufficient data were obtained to uncover several general properties of altered layer formation and growth. In addition, the data were used to find constants and diffusion coefficients for a first order altered layer model which can hopefully be improved on and used to calculate altered layer concentrations at different Hg pressure, target x-values, and sputtering times. It is probable that more data will be required to develop and further test the model so that it can be used for a range of Hg pressures and target x values. Certainly data for different applied rf power must be obtained to see if the model can be used at different sputter etch rates. Also of particular interest are the results for  $x = 1$  (CdTe) and  $x = 0$  (HgTe), which are required for study of PM targets, which consist of many small CdTe and HgTe targets in parallel. Note that these small targets have dimensions of the pressed powder particle size, average dimension about 7 microns, and that the altered layer may extend through an appreciable length of these targets during sputtering. NJIT is presently studying the altered layer properties calculated from the present computer model. For example, figure 20 shows the percent atomic composition of Hg versus depth for long sputtering times of the order of thin film runs. The data shown are for 1.6  $\mu\text{m}$  Hg pressure. The dip in Hg composition before it rises to its bulk value is seen. This dip is a result of influx of Hg from the target surface, which enhances the Hg concentration near the surface. The results show that the altered layer thickness for Hg increases as the one half power of time.

Defining the distance for the compositions to reach 90% of their final values as  $D^*$ , curves for distance\* versus sputtering time can be plotted as in figure 21. [The sputtering time value is actually the time after the surface reaches equilibrium, which is taken to be five minutes.] The Hg and Te curves follow each other closely and obey the equations,  $D^*_{\text{Hg}} [\mu\text{m}] = 1568.5 \sqrt{t[\text{sec.}]}$  and  $D^*_{\text{Te}} = 1470.1 t^{1/2}$ . The region over which the Cd concentration differs from its bulk value is smaller than the region for Hg and Te. Thus the  $D^*$  value for Cd increases more slowly than for Hg and Te, that is  $D^*_{\text{Cd}} = 963.4 t^{1/2}$ .

Some recently published work by other researchers is related to our research. Nitz et al (13) examined preferential sputtering of  $(\text{Hg}_{.8}\text{Cd}_{.2})\text{Te}$  with quasi-simultaneous SIMS (Secondary Ion Mass Spectrometry), AES (Auger Electron Spectroscopy), and XPS (X-ray Photon Spectroscopy). Solzbach et al (14) analyzed CdTe, HgTe and  $(\text{Hg}_{.8}\text{Cd}_{.2})\text{Te}$  surfaces with XPS

and AES after the surface were Ar<sup>+</sup> sputtered. Both sputtered with argon and found a Te and Cd enrichment and Hg depletion at the surface of the target, which is in agreement with the NJIT research. The work of Zozime(12) on the thin film composition of Hg-sputtered (Hg,Cd)Te films under different Hg pressure conditions supports our research results in that it shows that as the Hg pressure increases, Cd is depleted in the films and evidently on the surface of the polycrystalline (Hg,Cd)Te targets sputtered.

#### IV. Practical Findings

The following sections report on some of the most important practical findings of the research.

##### A. Material Availability and Costs

One of the main inducements for this research was the high cost of (Hg,Cd)Te bulk material, as much as \$2000 for a single crystal ingot slice. Often the direction of the research, e.g. the use of pressed-powder targets and the limit on the number and type of targets that could be studied, was determined by the high cost of material, particularly (Hg,Cd)Te ingots. Quotes of about \$4000 for a (Hg,Cd)Te polycrystalline ingot to fabricate one target were obtained from companies. The list of materials bought at the lowest available price for the grant, shown in the table below, point out relatively low cost of CdTe and HgTe, and the rising cost of HgTe. Although study of (Hg,Cd)Te ingot targets would have been quite useful for target studies as well as for thin film research, the research costs would have been prohibitive. Mr. Irwin Kudman, President of IR Associates, which had provided us with (Hg,Cd)Te material at a low cost in 1977, no longer had the interest in growing ingot material. Only the pressed-powder target approach and the gift of (Hg,Cd)Te ingot pieces by Santa Barbara Research Center and initial gifts by Infrared Associates enabled the fabrication of the large number of large-area targets necessary for the research program.

Cost of Materials

Material	Unit Price	Amount	Manufacturer	Date of Purchase
200g of Gallard-Schlesinger CdTe, 99.999% purity 325 Mesh powder	\$75/100g	\$150	Atomergic Chem. Corp., 100 Fairfield Ave. Plainview, N.Y. 11803, Mr. Howard Gary.	3/28/77
500g of HgTe, 5 9's purity	\$1/g	\$500	Infrared Associates P.O. Box 2436 Newark, N.J. 07114 Mr. I. Kudman	5/2/77
1 grown polycrystalline ingot of Hg <sub>.8</sub> Cd <sub>.2</sub> Te 5 9's purity	\$10/g	\$500	Infrared Associates	5/2/77

<u>Material</u>	<u>Unit Price</u>	<u>Amount</u>	<u>Manufacturer</u>	<u>Date of Purchase</u>
150g of non-optical grade CdTe powder	\$1.25/g	\$187.50	Two-Six Corp. Saxonburg Blvd. 16056	5/2/77
2 kilograms of HgTe polycrystalline pellets (.5 by .5 mm) 5 9's purity	\$2.35/g	\$4,700	Atomergic Chem Corp.	5/1/78
1 hot-pressed CdTe target, 5 inch dia. x 3/16 inch thick with MRC material		\$588	MRC, Pearl River, N.Y. 10965	11/21/79
150g CdTe non-optical grade powder 5 9's purity	\$1.55/g	\$232.50	Two-Six Corp.	9/29/80 8/21/81
300g HgTe polycrystalline pellets at 5 9's purity	\$3/g	\$900	Atomergics	8/5/81
150g CdTe non-optical grade powder	1.55/g	Quote	Two-Six Corp.	6/15/82

#### B. Fabrication and Mounting of Targets

As reported in the March-June 1979 Progress Report, target discs were made with an 80 ton press in the NJIT M.E. Lab. The maximum pressure that could be applied was limited by the rating of the 5.7 and 2.86 cm diameter stainless steel dies that NJIT purchased from Fred S. Carver Inc. (Manomonee Falls, Wisconsin). The densities of target discs versus applied pressure, disc thickness, and composition were studied to a limited extent. The following results were obtained for discs made by pressing powder ground from an  $x = 0.25$  solid solution ingot of (Hg,Cd)Te: a 0.15 cm thick, 2.86 cm diameter disc had a density of  $7.14 \text{ g/cm}^3$  with  $2.66 \cdot 10^8 \text{ Newtons/m}^2$  of applied pressure; a 2.82 cm diameter disc 0.3 cm thick had a density of  $6.7 \text{ g/cm}^3$  with  $2.61 \cdot 10^8 \text{ n/m}^2$  applied pressure. The powder for the S.S. target discs was made up of particles less than 50 microns with the mean particle dimension about 7 microns. [Note that the theoretical density of  $(\text{Hg}_{.75}\text{Cd}_{.25})\text{Te}$  material is  $7.6 \text{ g/cm}^3$ ].

Figure 22 shows the density of physical mixture discs made from powder mixtures with particles about the same size as those of the S.S. powder. Note the exponential rise in the applied pressure necessary to obtain denser targets. The thicknesses and diameters of the discs measured are shown along side each group of data points. It should be noted that for the same applied pressure, denser discs can be obtained with P.M. powder, probably because of the relative softness of HgTe versus (Hg,Cd)Te and CdTe. The density of a CdTe powder particle, 5.7 cm diameter disc was only  $5.04 \text{ g/cm}^3$  when made with an applied pressure of  $1.43 \cdot 10^8 \text{ n/m}^2$ . An experiment was done where two P.M. discs with the same dimensions, 0.15 cm thick and 2.86 cm diameter, but different composition were

pressed to almost the same density ( $7.16 \text{ g/cm}^3$  and  $7.22 \text{ g/cm}^3$ ). The  $7.16 \text{ g/cm}^3$  disc, with  $x = 0.25$  composition, required a pressure of  $2.94 \cdot 10^8 \text{ n/m}^2$  while the  $7.22 \text{ g/cm}^3$ , with  $x = 0.2$  composition and more HgTe particles, required a pressure of only  $2.64 \cdot 10^8 \text{ n/m}^2$  pressure. In another experiment, two  $x = 0.25$  discs were made with  $2.61 \cdot 10^8 \text{ n/m}^2$  applied pressure. The disc  $0.33 \text{ cm}$  thick had a density of  $5.88 \text{ g/cm}^3$  while the thinner  $0.3 \text{ cm}$  disc had a higher density,  $6.7 \text{ g/cm}^3$ . This dependence of density on thickness could be expected if one considers the random positioning of relatively soft more numerous HgTe particles with the harder CdTe particles.

More important than applied pressure in fabricating good targets, without cracks and soft areas, are the techniques for leveling the powder in the die before pressing and the techniques for removing the disc from the die after pressing the powder. As detailed in Bourne's thesis, a key factor is waiting several hours to let pressurized air escape from the die-disc interface before opening the die for removal of the disc. If this is not done, tiny and even large cracks appear on the target surface resulting in material from the target falling on growing films during sputtering.

An important factor to save research time and vacuum problems when doing sputtering research, is to be able to change targets without breaking the main target vacuum seal, which in the MRC 8800 requires 3 to 4 hours of labor. A new target design by Mr. Gabara was tested and implemented that enabled (Hg,Cd)Te discs mounted onto special, thin stainless steel backing plates, with recessed grooves for the discs, to be mounted into the front of the main, modified MRC backing plates. The total target system required 3 stainless steel pieces per disc, but provided a low thermal impedance for the dissipated target power. The details of the design are given in reference 3.

Some experiments were conducted to sinter (Hg,Cd)Te discs and to thus increase their density and homogeneity. This was considered desirable particularly to avoid the possibility of powder falling down from the disc onto films. The annealing of discs before sputtering is no longer thought to be necessary for the following reasons: a) the flaking off of deposition films from colder fixtures in the sputtering system, particularly the target shield, was found to be a major cause of falling material and preventive measures, preheating the system etc, were taken; b) x-ray measurements by Dr. Suchow showed that HgTe and CdTe particles in P.M. targets fuse together and the conditions for annealing during sputtering (target temperature, effective Hg pressure at the target surface) are probably more ideal and easier to obtain than by sintering discs in sealed off quartz tubes as outlined in the Oct-Dec. 78 and Dec.-March 79 ARO Reports.

### C. Purity of Target Material

The value of an electron microprobe scan for detection of chemical elements on the surface of sputtered target discs was proven when a few small particles of stainless steel were found. The presence of the particles was found to be related to chipping of the walls of a defective die. Since one of the sputtering technology objectives is to deposit uncompensated films with carrier concentrations in the  $10^{14}$ - $10^{16} \text{ cm}^{-3}$  range, it is desirable to have a minimum number of impurities in the target. The HgTe and CdTe material purchased for the discs was guaranteed to be only 5 nines pure. That purity will at best yield uncompensated films with impurities and carrier concentrations in the  $10^{17} \text{ cm}^{-3}$  range by normal sputtering techniques.

The lowest n-type carrier concentrations measured in films sputtered using the pressed-powder targets were in the  $10^{16} \text{ cm}^{-3}$  range and the electron mobilities were about one tenth the mobility of single crystal bulk material. Impurity type with concentrations in the  $10^{16} \text{ cm}^{-3}$  in the films can not be directly found. The films may be compensated and acceptor concentrations due to Hg or Cd vacancies along with impurities, could play a role in determining the measured carrier concentrations. At this point in the development of a (Hg,Cd)Te sputtering technology, it would seem to be important to test films sputtered using targets with HgTe and CdTe particles having six nines or better purity. [The alternative to obtain films with low extrinsic impurity concentrations is to use substrate bias to remove the impurities by slightly sputtering the more weakly-bonded impurities as the film is deposited. NJIT is presently studying this approach]. The very-pure material HgTe or CdTe might be obtained by zone refining according to Atomergics Chemical Corp.

As deposited sputtered films tend to be p-type, presumably due to either Hg or Cd vacancies, although the possibility of p-type extrinsic impurities also exists. It would be desirable to make targets deliberately doped with an n-type impurity, such as In, and see if as-deposited n-type material could be obtained by filling the vacancies with the n-type dopant. The pressed powder target approach enables impurities to be easily added to target disc.

#### D. Control of Hg Sputtering Gas Pressure

Sputtering at controlled values of Hg pressure is a difficult task which was increasingly important as thin film analysis results indicated the significant effects of Hg pressure on film properties. The Hg pressure was controlled by heating a stainless steel bottle outside the vacuum chamber (see figure 3) and controlling the temperature of the walls and fixtures inside the vacuum system. The mercury pressure was read with a CVC Pirani Gauge, GP 310, calibrated for Hg and checked occasionally by a Granville Phillips Series 224 Ionization Gauge.

The highest Hg pressure used for a film deposition run was  $2.0 \mu\text{m}$ . At this pressure using a 5.72 cm diameter target, and an R. F. input power of 200 watts, the deposition rate was still  $2\text{\AA}/\text{sec}$ . The Hg bottle had to be heated to  $46^\circ\text{C}$ , heated cathode cooling water had to be used (to prevent Hg condensation on the three targets not bombarded with Hg), and the coldest point measured inside the chamber was 7 to  $9^\circ\text{C}$ . The surface area of the Hg and the position of the Hg source with respect to the pumpout port appear to be factors influencing the maximum achievable Hg pressure. The highest pressure obtained in this research was only  $2.5 \mu\text{m}$ ; to obtain higher pressures, the temperature of the chamber and the Hg source must be raised and the temperature and thermal gradients throughout the vacuum system monitored using many thermocouples attached to a multi-thermocouple readometer. Heating of the chamber, when not carefully controlled, has produce vacuum leaks. It was found that the Hg pressure continued to be "pinned" at  $2.5 \mu\text{m}$  by cold spots inside the vacuum chamber, even though external wall temperatures were above  $50^\circ\text{C}$  and heated cathode cooling water was used. Both the film analysis and target research eventually made it clear that it was not desirable to have Hg pressure above  $1.3\text{--}1.5 \mu\text{m}$  for film deposition runs because of the depletion of Cd from the surface of (Hg,Cd)Te targets due to the influx of Hg. Therefore research to raise the Hg sputtering pressure above  $2.5 \mu\text{m}$  by heating the coldest fixtures

in the vacuum system was discontinued.

#### E. Measurements Using SEM Microphotographs

Equations for relating the distances and cone angles observed in angled SEM microphotographs to actual distances and angles were developed and described in detail in (3).

#### V. Conclusions and Suggestions for Future Work

The practical techniques for fabricating, mounting and sputtering low-cost, large area (Hg,Cd)Te sputtering targets were developed and advanced during this research. Targets composed of pressed powder mixtures HgTe and CdTe particles proved to be very attractive from the standpoint of low cost, introduction of impurities for doping sputtered films, and ease of adjusting the effective position of the target and thus obtaining sputtered films with any desired x-value. SEM topography studies of the target pointed out that the target erosion and the film deposition rates as well as topographical effects such as cone formation are dependent on powder size. The effect of the target shield was to bend the ion beam at the shield edge causing nonuniform (but perpendicular as evidence by the cone angles) ion dosage across the target; this enabled a large amount of information on the surface erosion process to be obtained with just one sputtering run. However, production (Hg,Cd)Te sputtering systems should be designed so that the shield is unnecessary. This would increase the lifetime of targets by a factor of 3 since the erosion rate of the groove in the outer rim of the target is about 3 times the erosion rate of the central portion of the target. Future work should include pressing a HgTe-CdTe powder mixture (with particles size less than 10-20  $\mu\text{m}$ ) in a 12.7 cm die; this disc could be presputtered in the vacuum system, if necessary, to obtain sufficient hardness.

A practical filtering method for obtaining small, noncontaminated particles, with no dimensions greater than 10-20  $\mu\text{m}$ , has to be found if cone formation is to be avoided and if target smoothness and maximum film deposition rate per target input power is to be obtained. Aside from causing the area over which sputtered films are uniformly thick to be less predictable and causing undesired film buildup on the triode box and other fixtures in the sputtering system (since material is sputtered obliquely from cones), deleterious effects due to the cones were not clearly identified. One undesirable effect may be slight changes in film composition as the target sputters, as the cones remain as their original composition while the smaller particles of CdTe and HgTe appear to interdiffuse. Further work remains to be done to see how complete the interdiffusion is and to see to what extent it is dependent on particle size, applied rf power to the target, Hg vapor pressure, and cooling rate of the target.



A detailed description of how Hg ion bombardment shapes the surface of (Hg,Cd)Te targets was obtained and was presented in reference 3 and outlined on pages 3 and 4 of this report. The most important results of scientific interest were as follows. The larger particles in the target powder are shaped into cones and sputter protect the material underneath. The process of sputter protection, due to the low sputtering yield of the larger particles at the cone tip, cause the large cones to recede away from the initial surface at a slower rate; cones of up to 150  $\mu\text{m}$  in height and 60  $\mu\text{m}$  wide were formed. Cones quickly erode away once the protective particle is sputtered through. The vertex angle of the cones decreased as the cones increased in height. The solid solution targets had only one vertex angle distribution, corresponding to (Hg,Cd)Te, while the physical mixture targets had two separate vertex angle distributions, one due to HgTe and a smaller angle distribution due to CdTe particles, which have a lower effective sputtering yield. The (Hg,Cd)Te vertex angle distribution is between the two other distributions, in support of the sputter protect theory.

Many suggestions for further scientific work have been given by Gabara(3). Some of these are: weight loss measurements and vertex angle distributions as a function of particle size; deliberate target indentations to obtain erosion profiles for finding the erosion slowness curve(3); further study of CdTe particle migration, as a function of target temperature; separate study of sputtering yields for HgTe, CdTe, and  $(\text{Hg}_{1-x}, \text{Cd}_x)\text{Te}$  targets; EDX compositional analysis of the small spherelike objects located at the outer rim and the sponge-like objects in the central portion of the target; sputtering for short periods of time to study motion of the sphere-like particles, the progression of steps down the sides of the cones, and the erosion and formation of cones.

The research on the compositional changes in triconstituent sputtered (Hg,Cd)Te targets was very difficult but important results were obtained. An experimental method was developed based on nondestructive ESCA measurements of target ingots, backetched at low temperature. This method enables reasonable data on composition versus target depth, sputtering time, and sputtering parameters to be obtained. The required sputtering etching, and ESCA experiments were expensive and time consuming. However, sufficient data were obtained from six sputtered targets to obtain constants for a first order model for the formation and growth of (Hg,Cd)Te altered layer. This model can be further developed so that the composition as a function of depth, time, and sputtering parameters (particularly Hg sputtering gas pressure and rf target input power) can be calculated for  $(\text{Hg}_{1-x}, \text{Cd}_x)\text{Te}$  targets, with any compositional parameter  $x$ .

From the experimental data, general conclusions on the altered layer growth and formation were drawn, as presented on pages 11 and 12. The most important findings were the depth and growth rate of

the altered layer (for 200 watt input power), the time to reach steady state surface behavior, and the steady state surface concentrations for Hg and Cd. It was found that with 1 mtorr Hg sputtering gas pressure that Hg and Cd are depleted at the surface while the concentration of Te is enhanced. However, as the Hg sputtering gas pressure is increased to 1.6 mtorr, the Hg surface concentration increases to almost the value in the bulk while Cd is almost depleted. This result correlates with the poor film results for Hg pressures greater than 1.3 mtorr. The data indicated that a linear dependence of the influx of Hg into the target surface can be assumed, an assumption which can be related to Henry's Law. Another interesting result, found by both experiment and computer model, was that the distance over which Hg and Te change to their bulk values is greater than the distance over which cadmium changes. The different altered layer thicknesses for the three components were calculated by computer and found to be of the order of 1 micron for 1 hour of sputtering, as shown in figures 21 and 22. Another interesting result, due to the influx of Hg from both the front surface and bulk region, was the dip in Hg concentration that propagates from the surface with sputtering time.

There are several limitations to the conclusions that can be drawn from the (Hg,Cd)Te altered layer research completed so far. They will be brought out in the following questions and suggestions for future research. Some of this research is already underway at NJIT.

1) How accurate are the three  $K_i$  constants and three diffusion coefficients used in the computer model? More experimental data for  $x = 0.2$  ingot targets would be useful to test the accuracy of the constants and coefficients used. Is it necessary to assume the diffusion coefficients are a weak function of Hg pressure? Calculations are presently being made to answer this question. Would the values for the constant and coefficients depend strongly on target composition? On rf input power? On target temperature and cooling water temperature and flow? Data for different target compositions and input power are required.

2) Are the surface layers amorphous during sputtering? The bulk region is obviously crystalline. What is the crystallinity and defect concentrations throughout the altered layer? Electron diffraction measurements of the samples already back etched should give information on these questions. Hg has diffused into the target and forced out Cd. Has the Hg gone into the lattice substitutionally or interstitially?

3) Can a computer model be developed that will predict the Hg pressure that will give target surface concentrations for Cd, Hg, and Te that would be ideal for film growth? The growth rate of the film depends not only these surface concentrations but also the sputtering yields of these elements, their mean free paths through the Hg plasma (which are probably greater than the target to substrate distance)

and the sticking coefficients at the substrate. More data for different Hg pressures are necessary to determine more accurately at what pressure the Cd surface concentration drops to low values that will not yield the Cd film concentrations necessary for stoichiometric films. Data relating film and target surface concentrations can be obtained. In fact, NJIT has built substrate masking apparatus that would enable these data to be taken.

4) What is the behavior of HgTe and CdTe targets? Can the computer model correctly predict the surface concentration values of the Hg, Cd and Te elements and correlate the behavior with film deposition results for physical targets mixture?

5) The present samples should be etched further to obtain direct experimental evidence of the depth of the altered layer for 1 mtorr Hg pressure.

Mercury Cadmium Telluride sputtered target research in the immediate future should be closely related to the problems associated with obtaining high-quality thin films by sputtering. Priority should be given to those experiments that will speed the development of a practical thin film (Hg,Cd)Te sputtering technology. There presently is a need to obtain as-deposited films that are n-type so that the as-deposited film crystalline quality can be indirectly evaluated by measuring the electron mobility values for uncompensated n-type films. Therefore immediate emphasis should be placed on the preparation and sputtering of pressed- powder targets with column III elements, such as Ga, In, and Al.

#### Acknowledgement

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# REFERENCES

1. R. H. Cornely, L. Suchow, T. Gabara and P. Diodato, IEEE Trans. Electron Devices ED-27, 29 (1980).
2. R. H. Cornely, L. Suchow, M. Mulligan, T.-O. Chan, R. Haq and C. Mehta, J. Vac. Sci. Technol., 18(2), March, 1981.
3. Thaddeus Gabara, Study of Topographical Changes in Ion-Bombarded Target Surfaces of Mercury Cadmium Telluride, MSEE thesis New Jersey Institute of Technology, May, 1980.
4. Robert Bourne, Study of Compositional Changes (Altered Layer) in (Hg,Cd)Te Targets Sputtered with Hg Vapor, MSEE thesis New Jersey Institute of Technology, May 1982.
5. Stewart, A.D.G., Thompson, M. W., "Microtopography of Surfaces Eroded by Ion-Bombardment, J. Mat. Science, vol. 4, 1969, pp. 59-60.
- 5a. Witcomb, M.J., "Franks Kinematic Theory of Crystal Dissolution Applied to the Prediction of Apex Angles of Conical Ion-Bombardment Structures", J. Mat. Science, vol. 9, 1974, p. 551-563.
6. Barber D. J., Frank, F. C., Mass M., Steeds J. W., Tsong, I. S., "Prediction of Ion-Bombarded Surface Topographies Using Frank's Kinematic Theory of Crystal Dissolution:", Journal of Mat. Science, vol. 8 1973 pp. 1030-40.
7. Kaufman, H. R. and Robinson, R.S.S., "Ion Bean Texturing of Surfaces", J. Vac. Sci. Technol. vol. 16, 1979, pp. 175-178.
- 7a. Wilson, I. H., Ion Surface Interaction, Sputtering and Related Phenomena, London: Gordon and Breach, 1973, pp. 217-225.
- 8) The sputter protect theory of cone formation is based on the following articles discussing the seeding of a sputtering target with impurities and the effect on cone formation:
- 8a. Wilson I.H., Kidd, M.W., "A Study of Cones Developed by Ion- Bombardment of Gold", J. Mater. Sci., vol. 6, 1971, pp. 1362-1366.
- 8b. Witcomb, M.J., "Frank's Kinematic Theory of Crystal Dissolution Applied to the Prediction of Apex Angles of Conical Ion-Bombardment Structures", ibid, vol. 10, 1975, pp. 669-682.
- 8c. Wehner, G. K., and Hajicek, D.J., "Cone Formation on Metal Targets During Sputtering", J. Mater. Sci., vol. 42, 1971, pp. 1145-49.
- 8d. Kaufman H.R., and Robinson, R.S., "Ion Bean Texturing of Surfaces", J. Vac. Sci. Technol., vol. 16, 1979, pp. 175-78.
- 8e. Witcomb, M.J., "The Development of Ion-Bombardment Surface Structures on Stainless Steel", J. Mater. Sci., vol. 9, 1974, 551-563.

9. Richard E. Honig, "Surface and Thin Film Analysis of Semiconductor Material" Solid State Films, vol. 31 (Switzerland: 1976) pp. 89-122. Additional information in ASTM Standardization News (2/78), p. 18.
10. Patterson and Shirn, J. Vac. Sci Technol., 4(6), 1967 p. 343-346.
11. W. Jost, Diffusion: In Solids, Liquids, Gases N. Y.: Academic Press, (1960), pp. 75-93.
12. A Zozime et al. "Growth of Thin Films of Cadmium Mercury Telluride ( $\text{Cd}_x\text{Hg}_{1-x}$ )Te Solid Solution by Cathode Sputtering in a Mercury Vapor Plasma" Thin Solid Films, 70(1) (1980), pp. 143.
13. H.M. Nitz et al., "Quasisimultaneous SIMS, AES, XPS, and TDMS Study of Preferential Sputtering, Diffusion, and Mercury Evaporation in  $\text{Cd}_x\text{Hg}_{1-x}\text{Te}$ " Surf. Sci., vol. 104 (1981), pp. 374.
14. U. Solzbach et al. "Sputter Cleaning and Dry Oxidation of  $\text{Hg}_{0.8}\text{Cd}_{0.2}\text{Te}$  Surface" Surf. Sci., vol. 97 (1980), pp. 194.

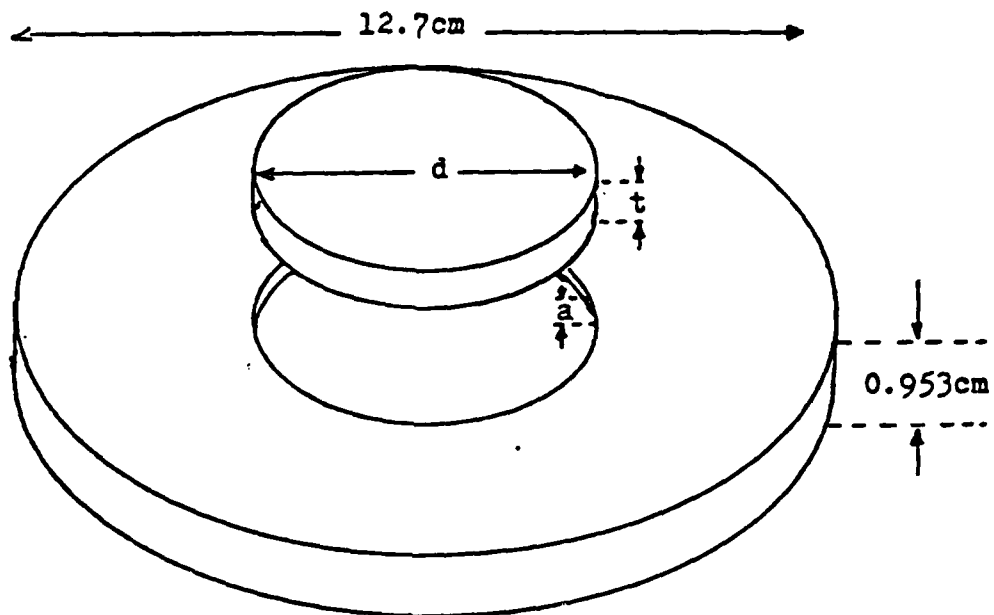


Figure 1 A disc and the associated backing plate with a recess of depth  $a$  which is used to center the disc

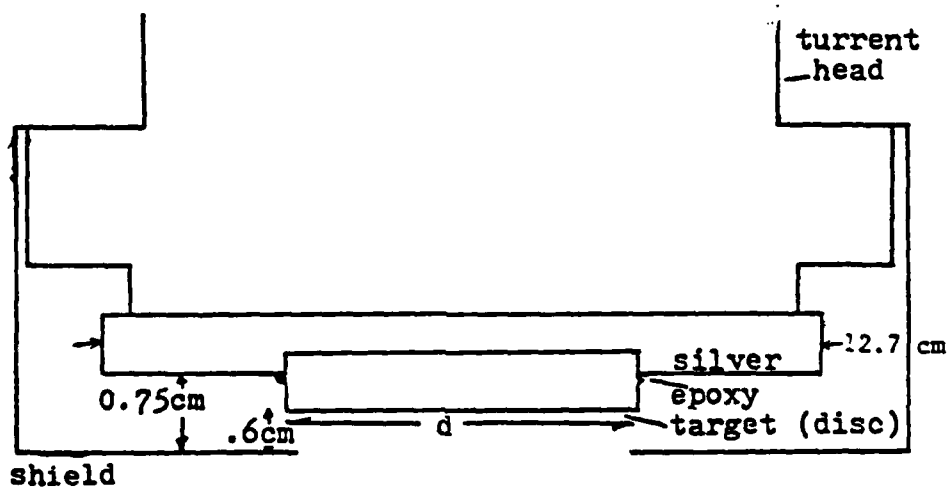


Figure 2 A cross sectional view of the way the 12.7cm backing plate with epoxied target is positioned in the sputtering system

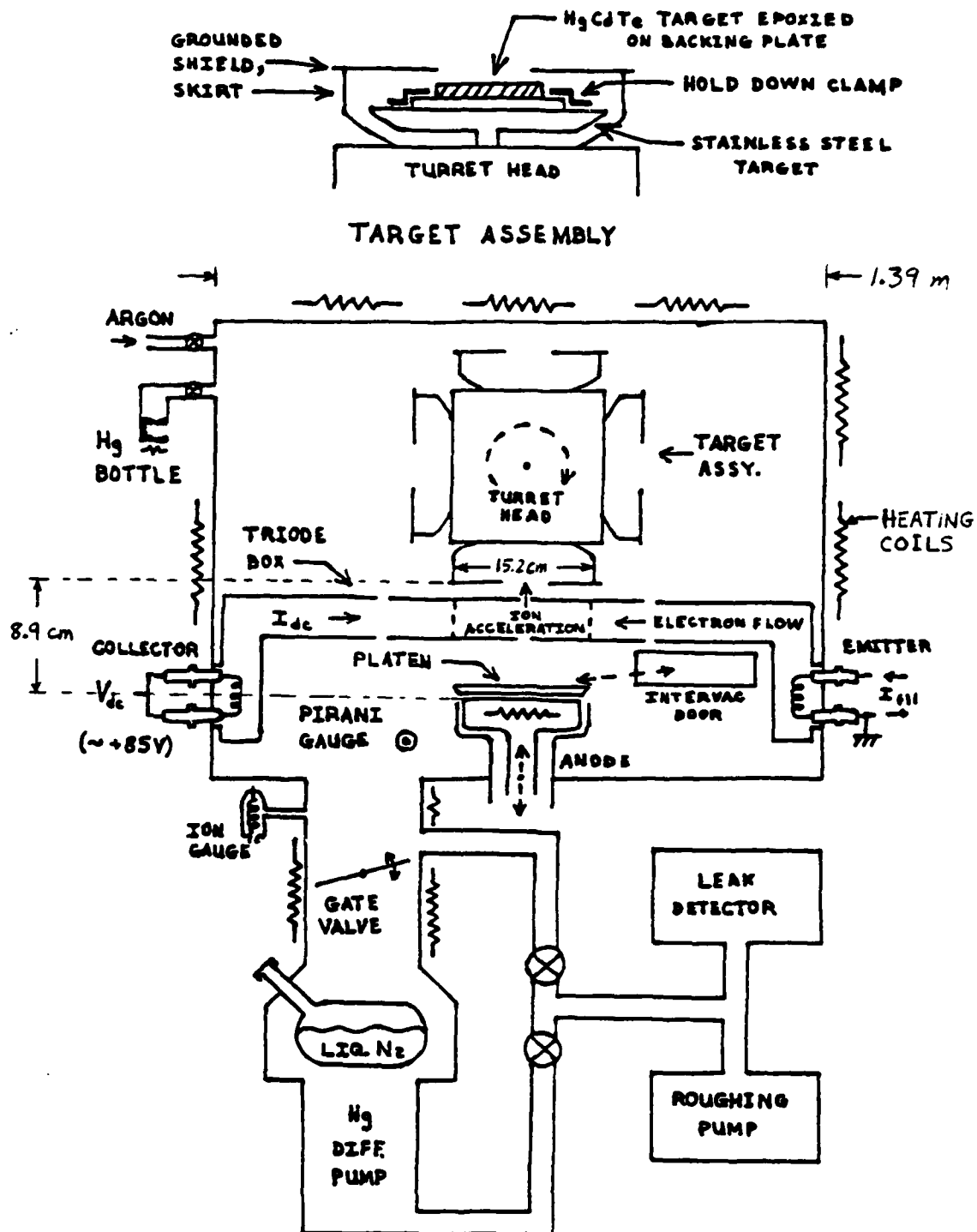


Figure 3 Modified MRC 8800 Sputtering System.

Eroded depth of surface and height of the largest cones,  $\mu m$

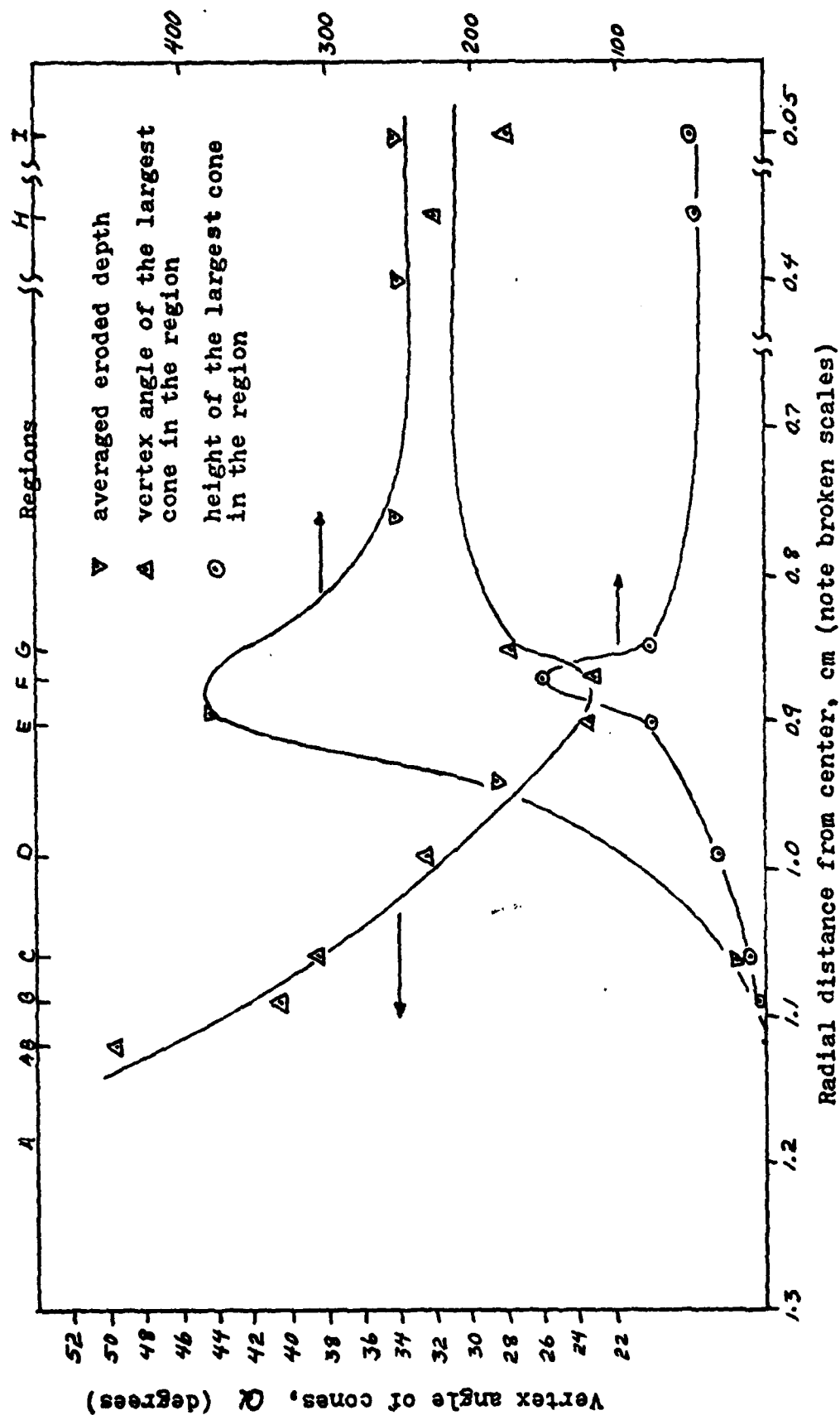


Figure 4 The average eroded surface profile for the solid solution target along with the distribution of the largest cones and their corresponding vertex angles in different regions



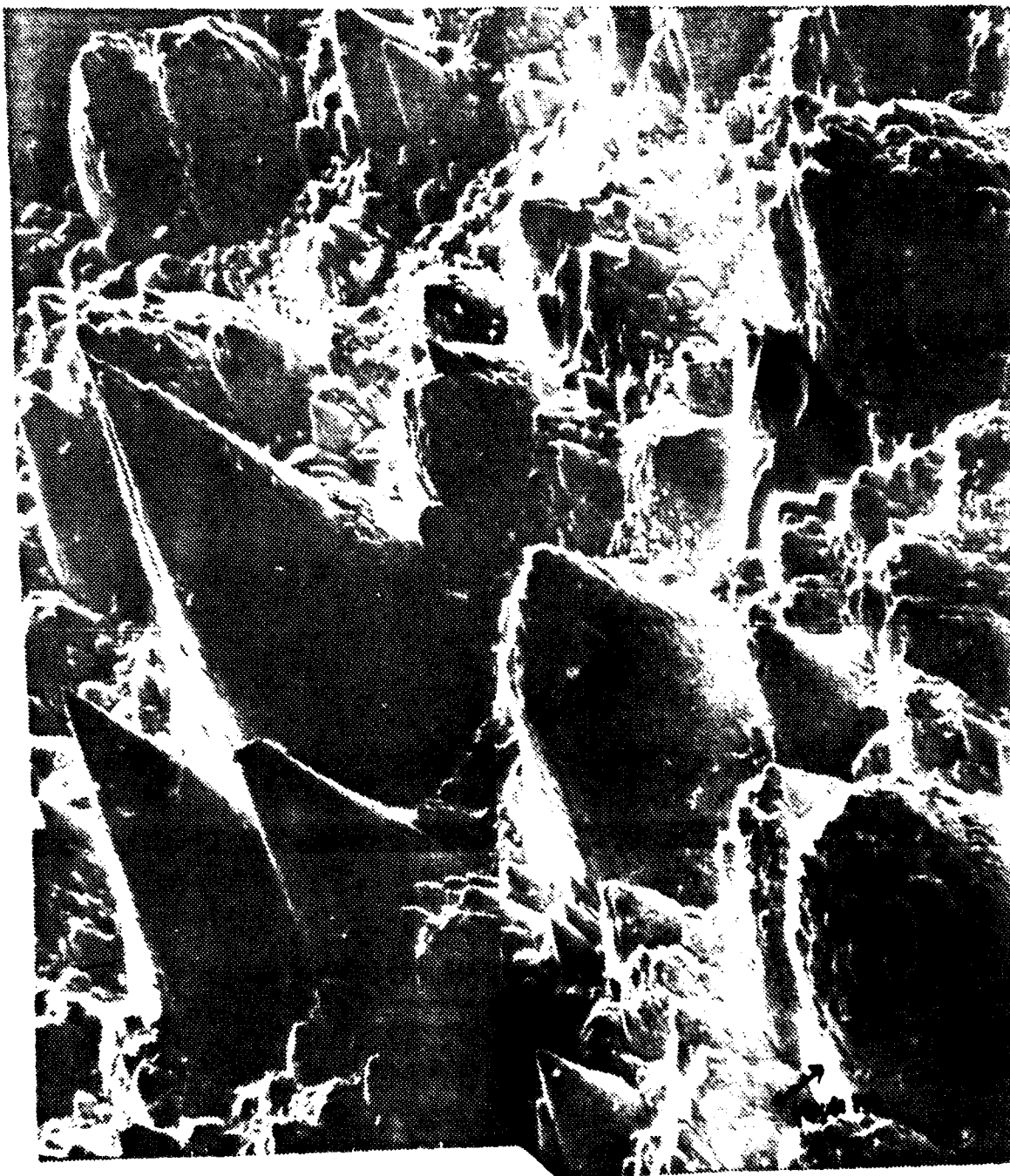


Figure 1. Montage of area F depicting the largest cones and smaller vertex angles of the entire surface. The deterioration of the peaks of some cones are also noted. (1000x)

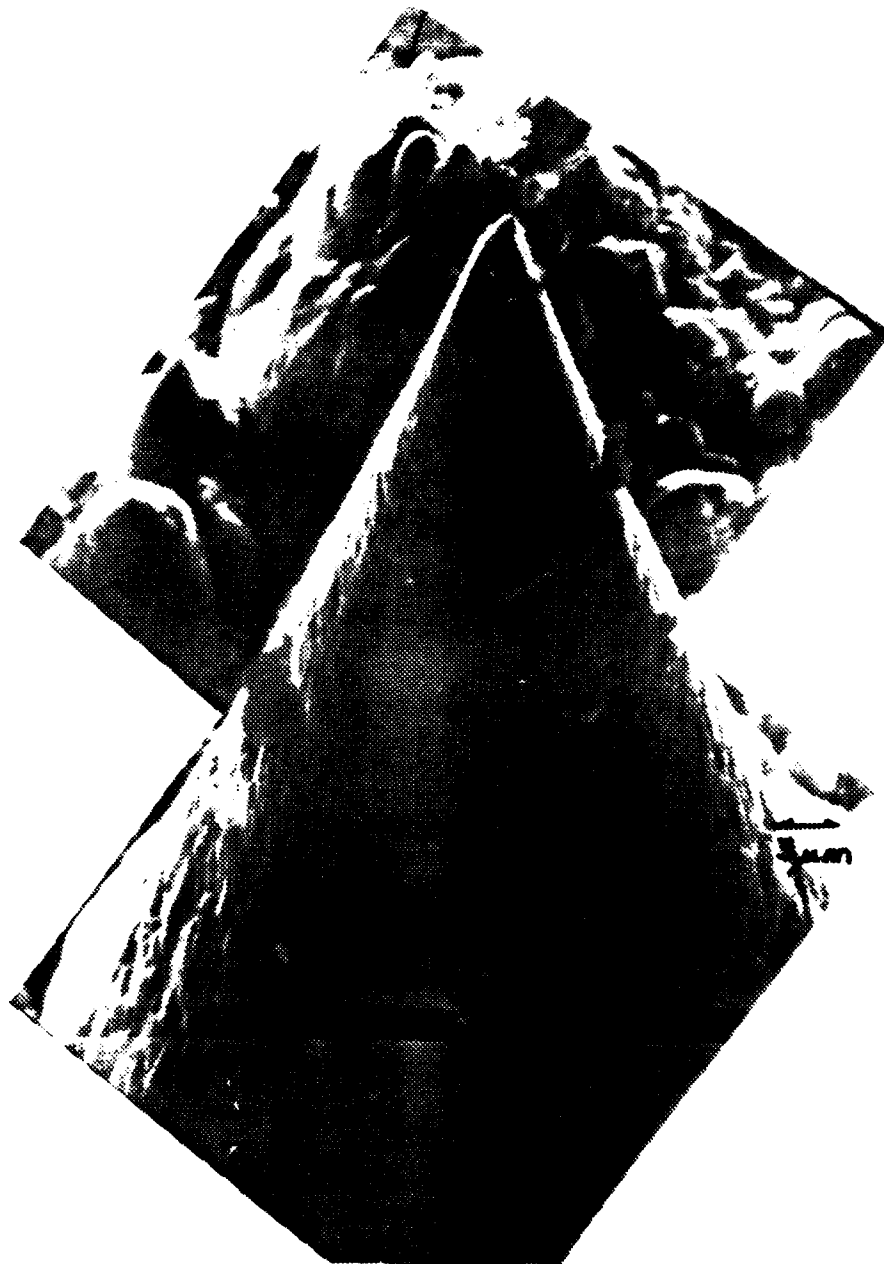
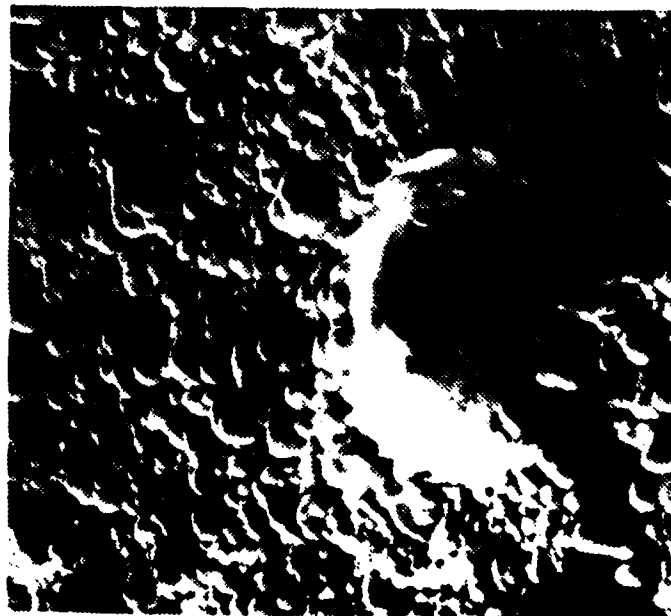
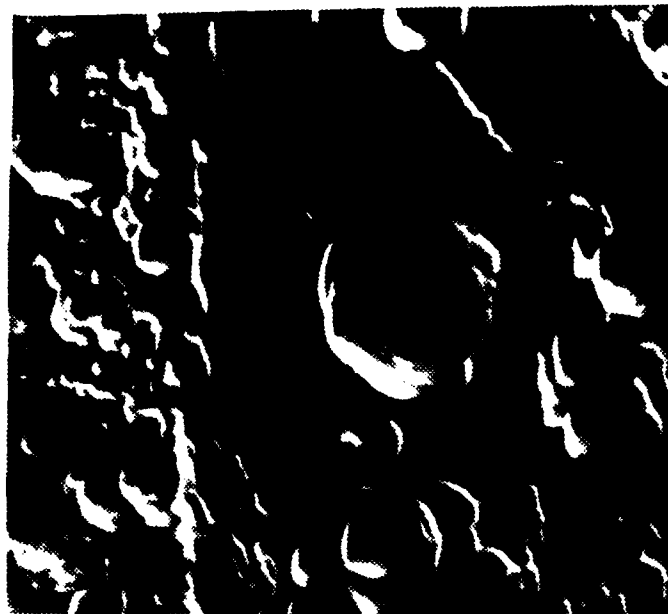


Figure 1. Partial view of a cone with its side covered with sand. The vertex angle of the cone is about  $38^\circ$ , 300%.

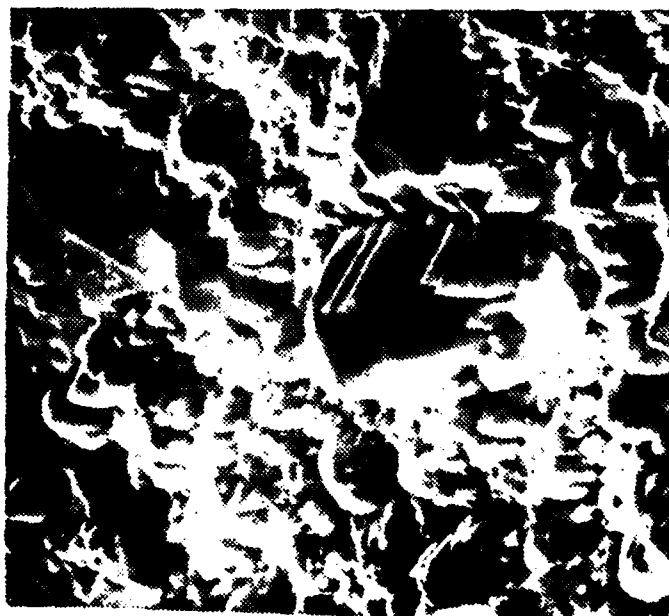


(a)

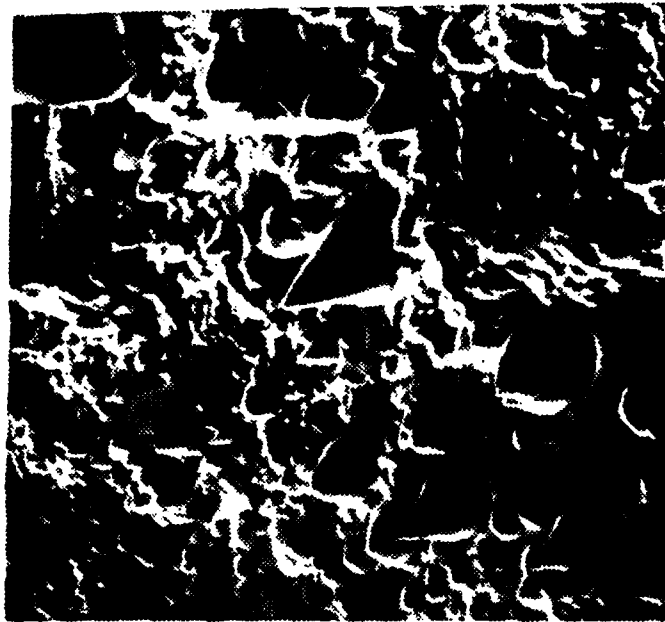


(b)

Figure 7 Close-up micrograph of two different areas of region AB depicting a cone-shaped impurity and cones forming on a large particle, (a) 5000X, (b) 10,000.



(a)

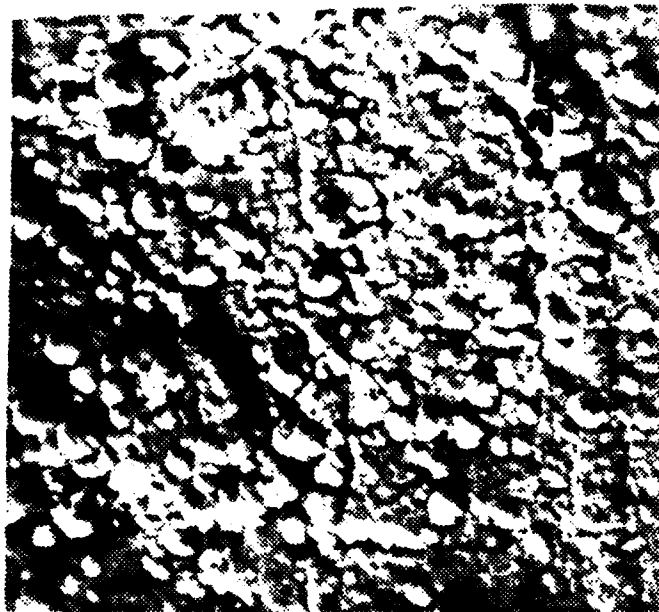


(b)

Figure 8 Close-up scanning micrographs of region B. (a) depicting a large particle forming into a high plateau, 3000X. (b) many cones forming on and off the large particles, 5000X.



(a)



(b)

Figure 9 Scanning micrograph of region A revealing the unspattered surface of the pressed powder physical mixture  $(\text{Hg}_{0.75}\text{Cd}_{0.25})\text{Te}$  target. (a) 1000X, (b) 5999X

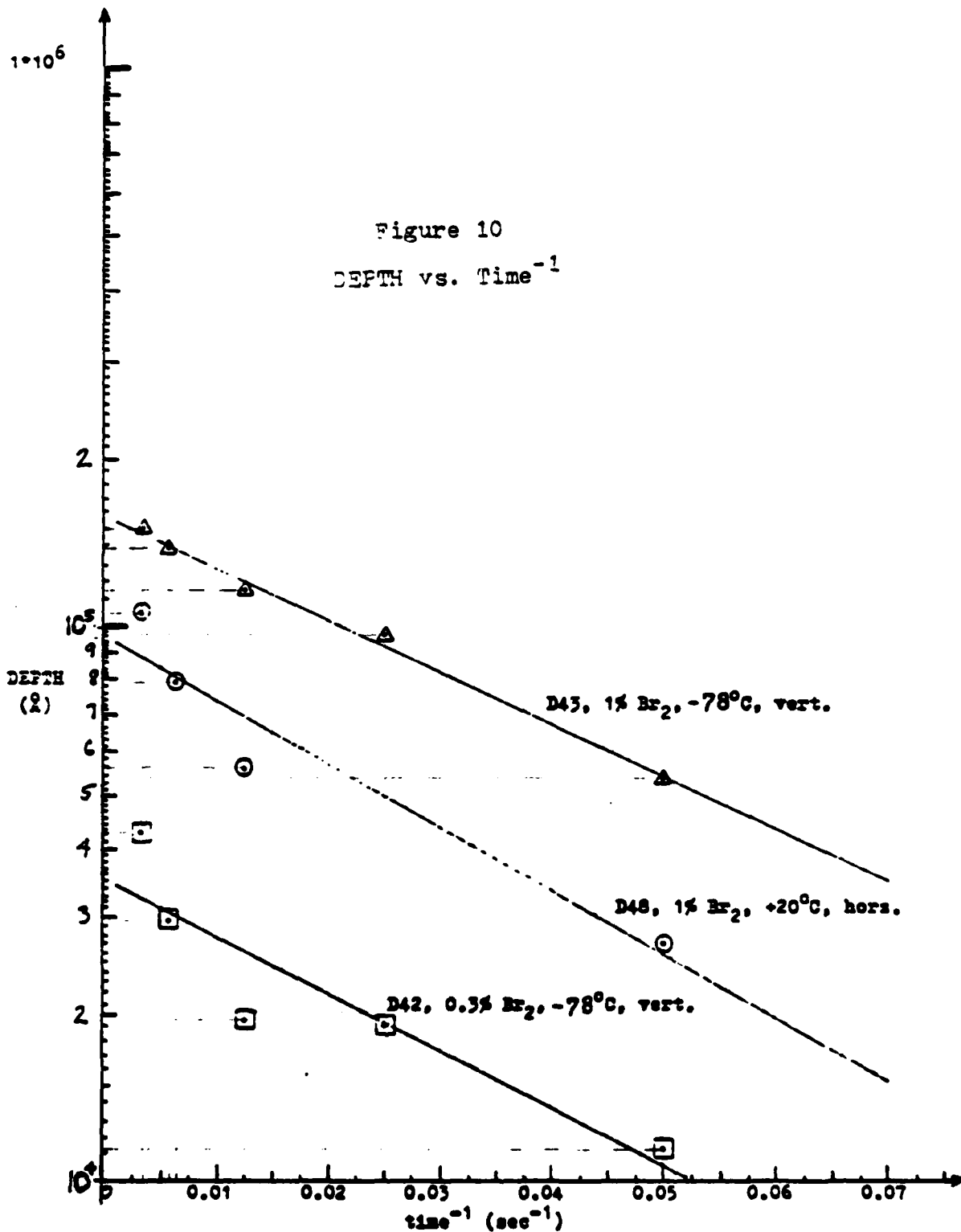


FIGURE 11-a

## ADJUSTED and NORMALIZED

Sample name	Depth O A	Date	Time (min.)	Press. ( $\mu$ )	Te (adjusted & normalized)	Cd	Hg
D77-5K	0	9/8	1	1.0	62	29	9
D77-5C	250	"	"	"	77	6	17
D77-5J	500	"	"	"	86 - 81	0 - 5	14 - 13
D77-5E	750	"	"	"	82	7	11
D77-5F	1000	"	"	"	78	6	16
D77-5G	1250	"	"	"	79	6	15
D80-3IB	0	9/8	2	1.0	83	3	14
D80-3L	250	"	"	"	75	7	18
D80-3LA	500	"	"	"	85 - 83	0 - 2	15 - 15
D80-3J	750	"	"	"	77	5	17
D80-3H	1000	"	"	"	78	8	14
D79-6L	0	9/8	3	1.0	86	2	12
D79-5I	250	"	"	"	87	1	12
D79-5H	500	"	"	"	88	1	11
D79-6I	750	"	"	"	86	3	12
D79-6K	1000	"	"	"	87	2	12
D79-6M	1250	"	"	"	88	3	9
D79-5I	1500	12/4	"	"	85	1	14
D79-6I	2000	"	"	"	85	2	13
D79-6L	2500	"	"	"	83	3	14
D79-6H	3000	"	"	"	83	1	15
D79-6K	3500	"	"	"	85	1	14
D79-6M	3750	"	"	"	69	17	14
D86-5M	0	12/4	5	1.25	85	1	14
D86-2K	500	"	"	"	87	2	12
D86-5L	1250	"	"	"	81	5	14
D86-2M	2500	"	"	"	79	6	15
D86-5D	3750	"	"	"	77	3	21
D74-6E	0	6/22	1	1.6	53	23	24
D74-6F	250	"	"	"	53	23	24
D74-6H	500	"	"	"	44	20	36
D74-4C	750	"	"	"	54	25	21
D74-4D	1000	"	"	"	56	20	24
D74-4K	1250	"	"	"	59	17	24
D67-2G	0	2/27	5	1.6	64	0	36
D67-2G	250	"	"	"	60	0	40
D67-1I	500	"	"	"	57	0	43
D67-1K	750	"	"	"	56	0	44
D67-2F	1000	"	"	"	63	0	37
D67-2G	1250	6/22	"	"	61	11	28
D67-1I	1750	"	"	"	61	8	32
D67-2E	2750	"	"	"	57	15	28
D67-1K	3250	"	"	"	51	12	37

FIGURE 11-b

STRUCTURE PROBE INC., ESCA DATA

Sept. 8, 1981

Technical Report #

Estimated Atomic Concentration (%)

sample name	depth O A	Te	O	Cd	N	C	Hg	normalized for:		
								Hg	Cd	Te
reference samples										
4JB	ref.	0.35	13.68	0.57	1.05	80.87	3.47	79	13	8
4JA	# 0	1.63	17.28	0.26	-	77.63	3.19	63	5	32
samples from D77										
5K	0	0.30	16.11	1.13	3.56	78.38	0.52	27	58	15
5C	250	0.67	19.43	0.42	3.02	74.64	1.82	63	14	23
5J	500	0.30	16.67	-	3.61	78.80	0.62	67	0	33
5E	750	1.91	19.90	1.34	1.50	72.26	3.09	49	21	30
5F	1000	0.60	18.29	0.36	4.25	74.96	1.54	62	14	24
5G	1250	0.56	21.96	0.37	1.15	74.60	1.35	59	16	25
samples from D80										
3IB	0	0.51	15.13	0.16	3.40	79.70	1.10	62	9	29
3L	250	0.81	16.80	0.64	-	79.42	2.33	62	17	21
3IA	500	0.43	14.13	-	4.88	79.61	0.95	70	0	30
3J	750	0.41	14.30	0.24	3.36	80.55	1.14	64	13	23
3H	1000	0.40	13.45	0.33	2.23	82.67	0.92	56	20	24
samples from D79										
6L	0	6.41	17.68	1.14	4.40	59.77	10.61	58	6	35
5I	250	7.18	12.28	0.56	3.29	64.68	12.10	61	3	36
5H	500	0.57	14.49	0.49	3.90	72.38	8.15	59	3	39
6I	750	5.01	15.09	1.23	2.31	67.20	8.35	57	8	34
6K	1000	5.89	17.71	0.97	4.89	60.49	10.04	59	6	35
6M	1250	6.06	13.46	1.52	-	70.89	8.07	52	10	39



FIGURE 12

RUN # 5

DISC# 80

July 21, 1981

1:33 PM

Sputtering time (Min.):

two

Mercury pressure (u):

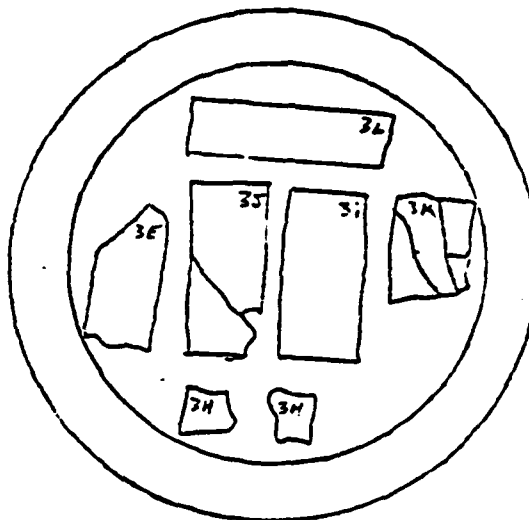
1.0

r.f. power (W):

200

Ionized plasma:

Hg



MRC-8800 triode settings & readings

Gate valve (deg.) 14

Cathode voltage (V) 1300

Denton power meter:

forward (W) 200

reflected (W) 20

Triode voltage supplies:

triode current (A) 5

triode voltage (V) 85

triode fil. volt. (V) 64

Power Amp:

grid (units) 0.03

volt (units) 0.43

fil. (units) 0.46

plate current (units) 0.16

r.f. coupling dial settings:

input (units) 0302

load (units) 1958

Anode temperature:

set (V) 22

temp. (deg.C) 250

Chamber temperatures:

front left (deg. C) 65

top (deg. C) 125

front right (deg. C) 94

D77

FIGURE 13 Percent Atomic Concentrations Versus

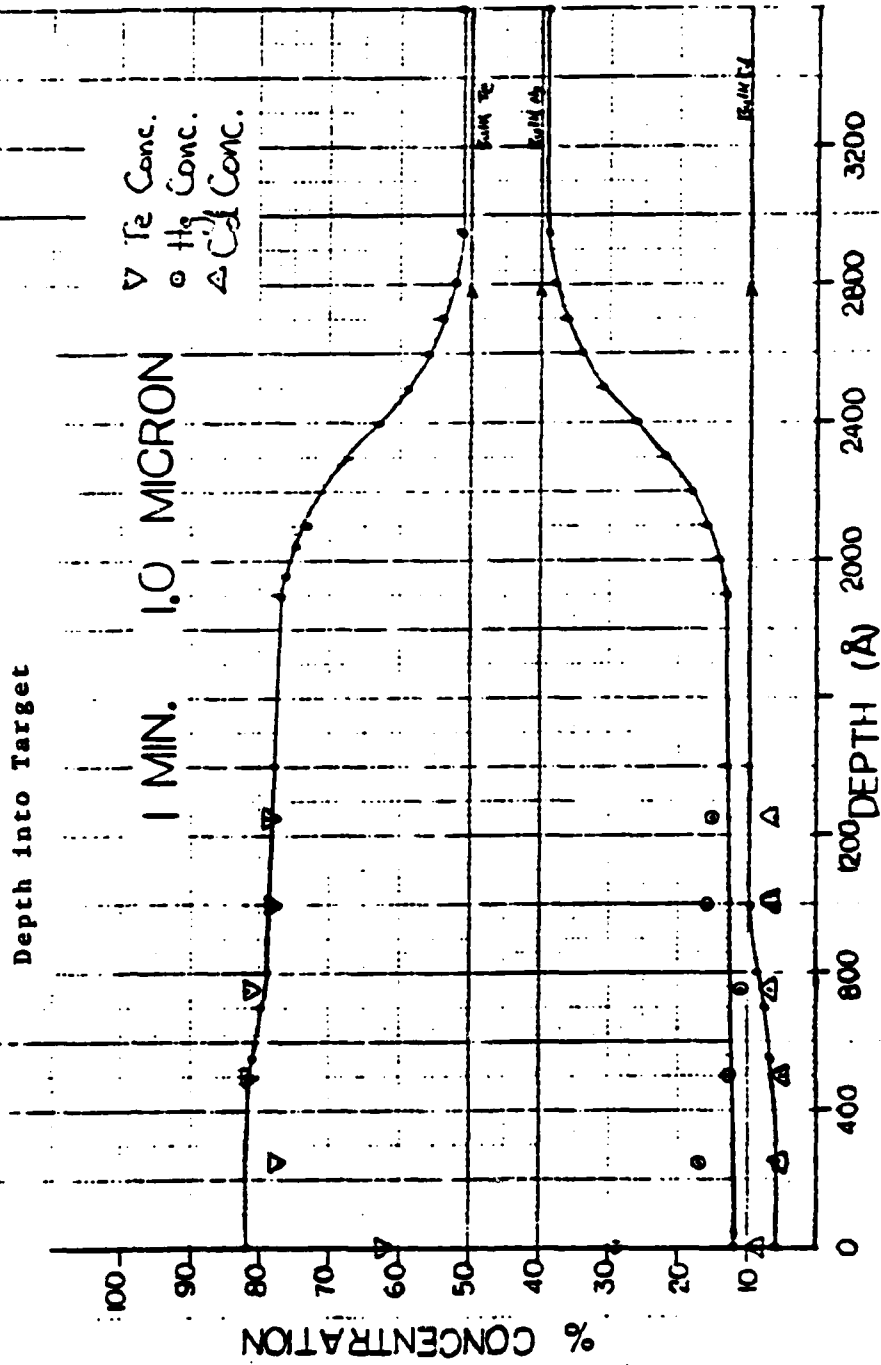


FIGURE 14 Percent Atomic Concentrations Versus  
Depth into Target

D80

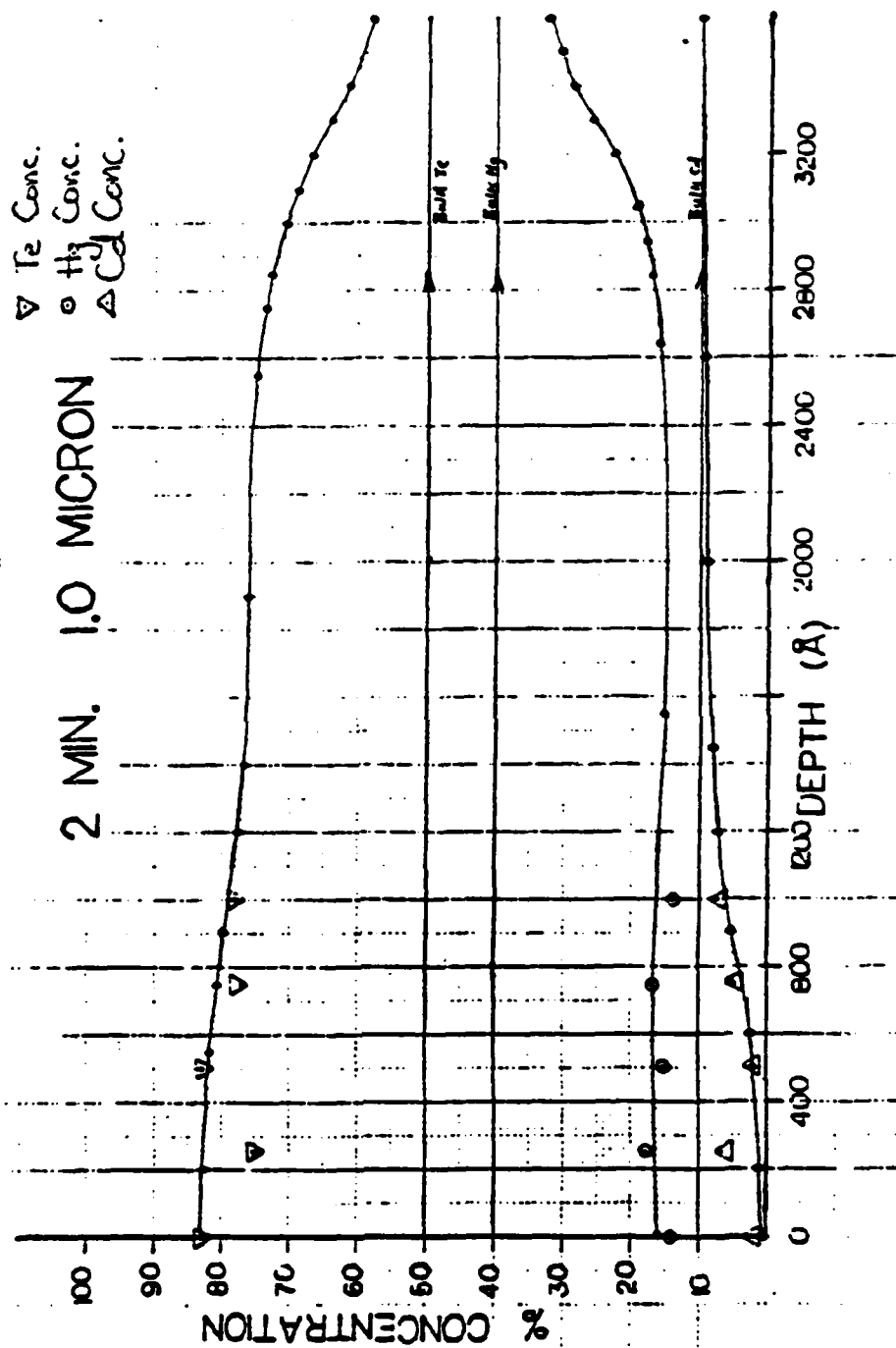


FIGURE 15 Percent Atomic Concentrations Versus Depth into Target

D79

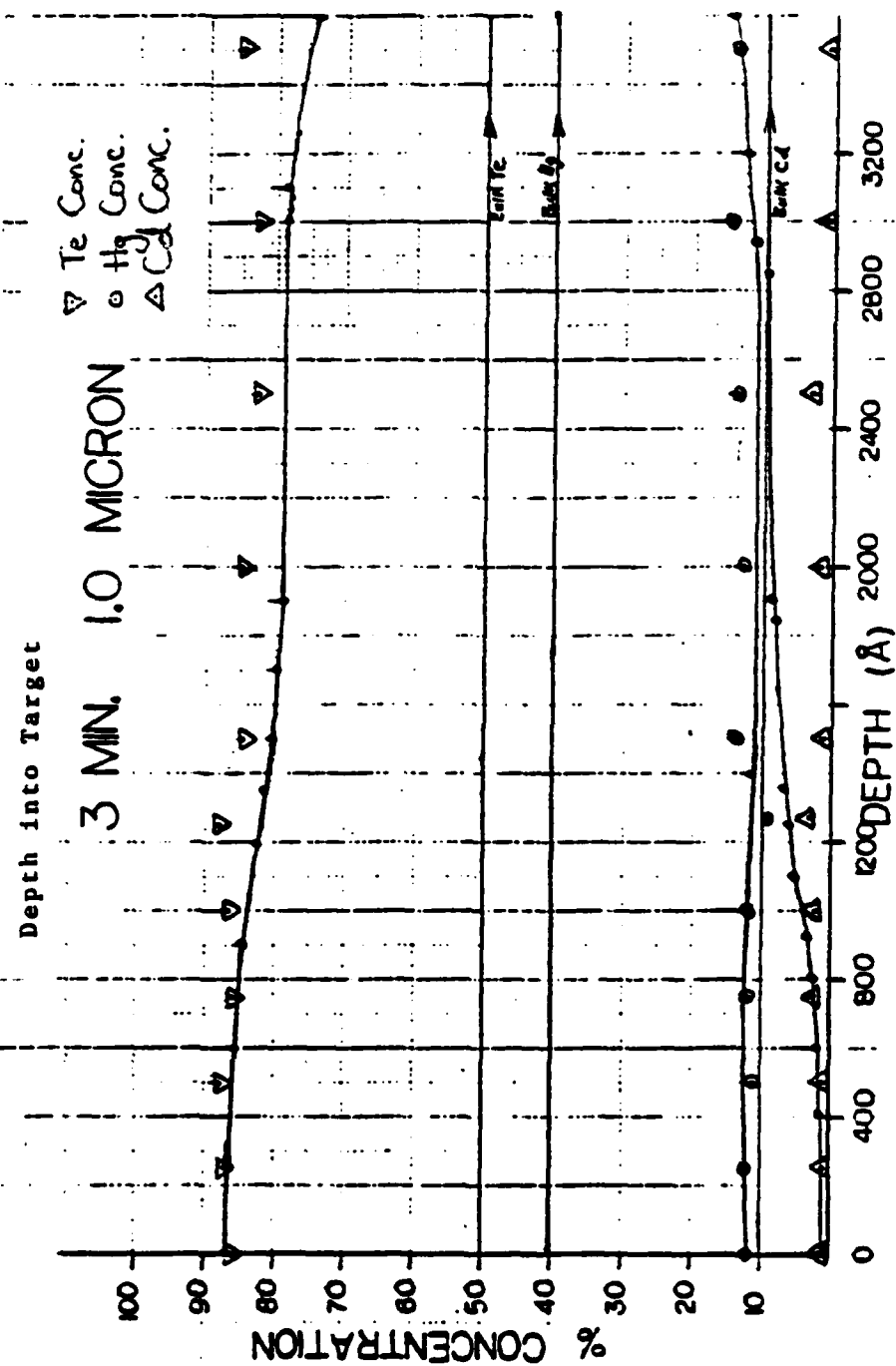


FIGURE 16 Percent Atomic Concentrations Versus

D86

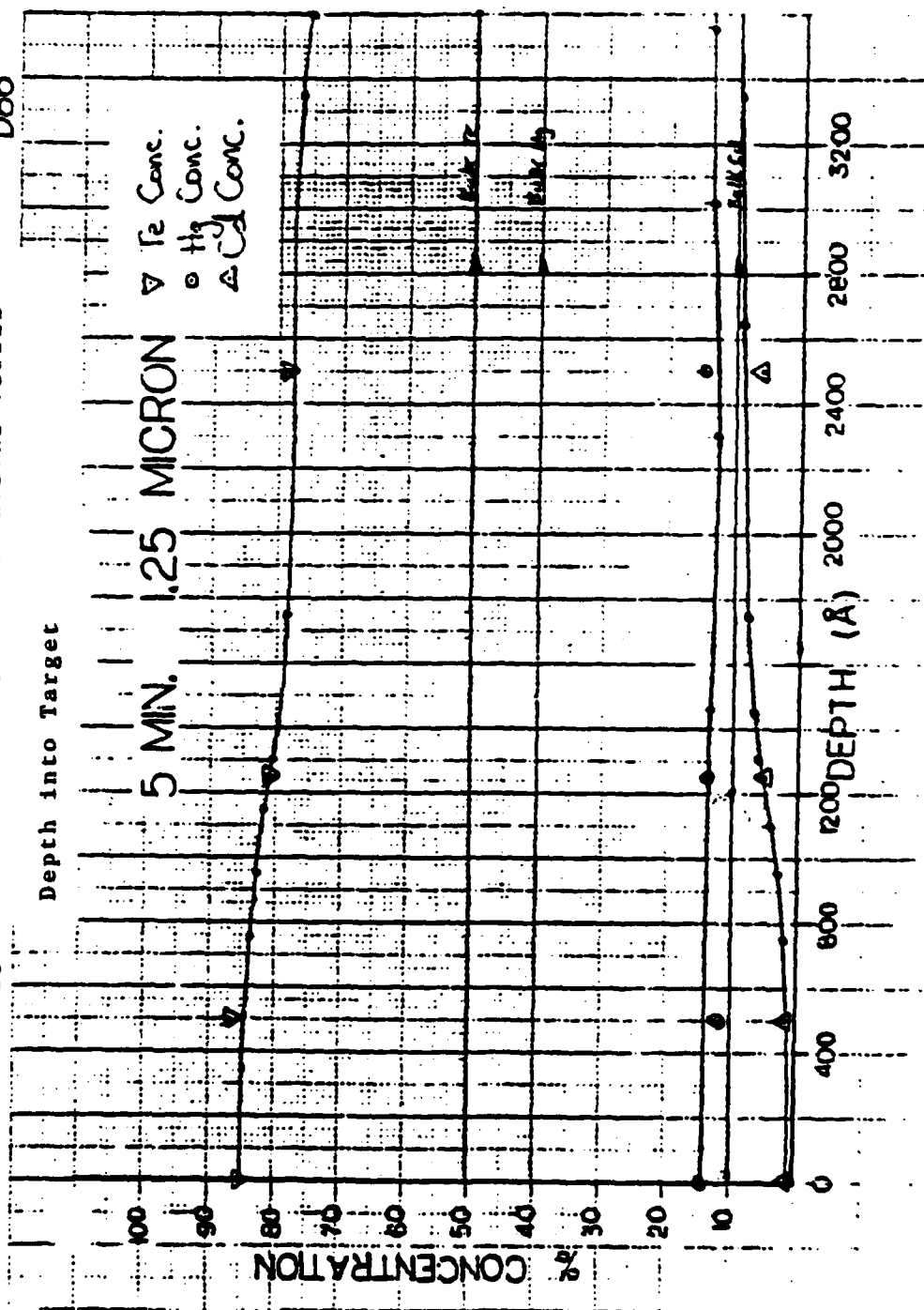


Figure 17 Percent Atomic Concentrations Versus

D74

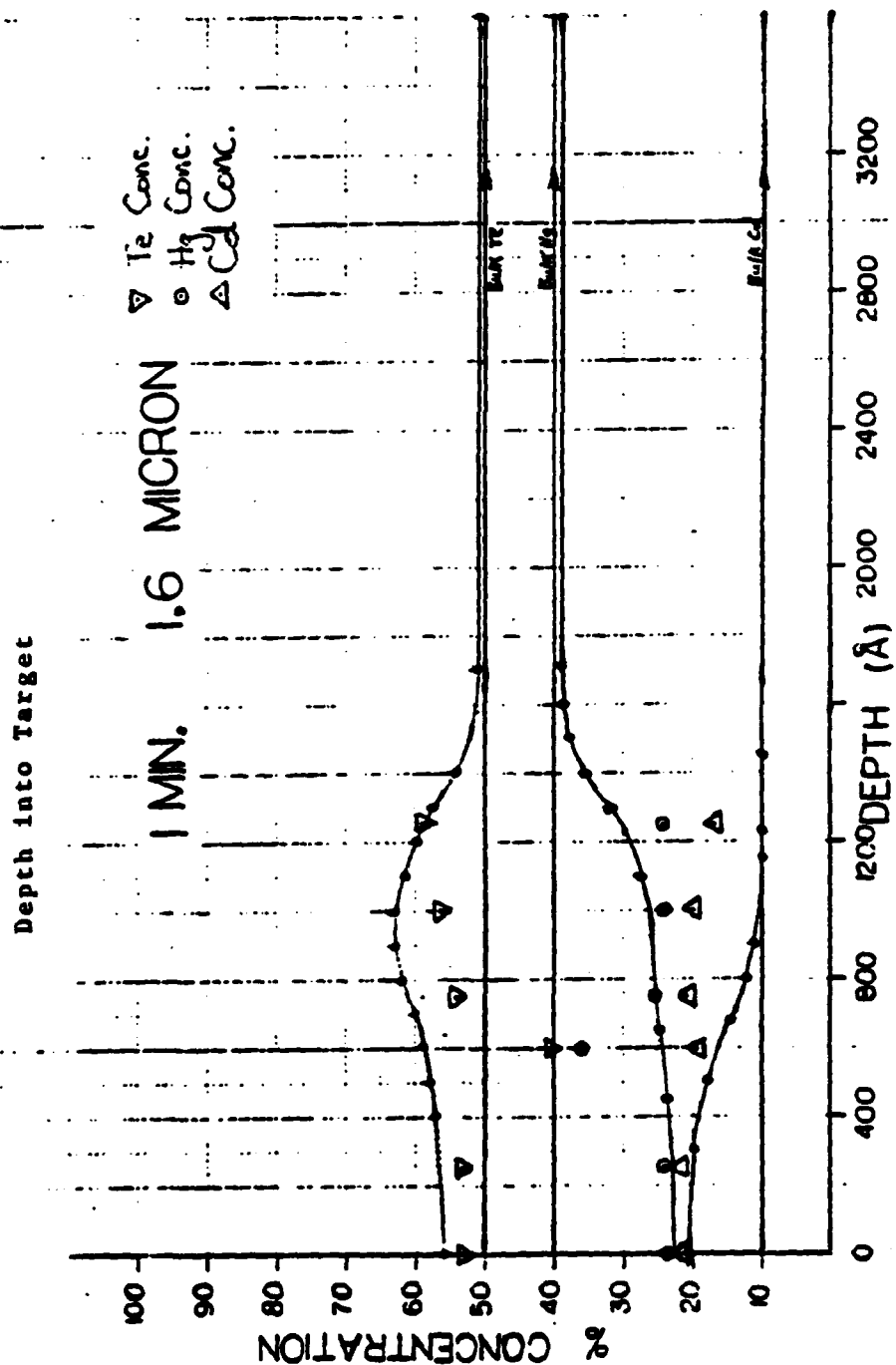


Figure 18 Percent Atomic Concentrations Versus Depth into Target D67

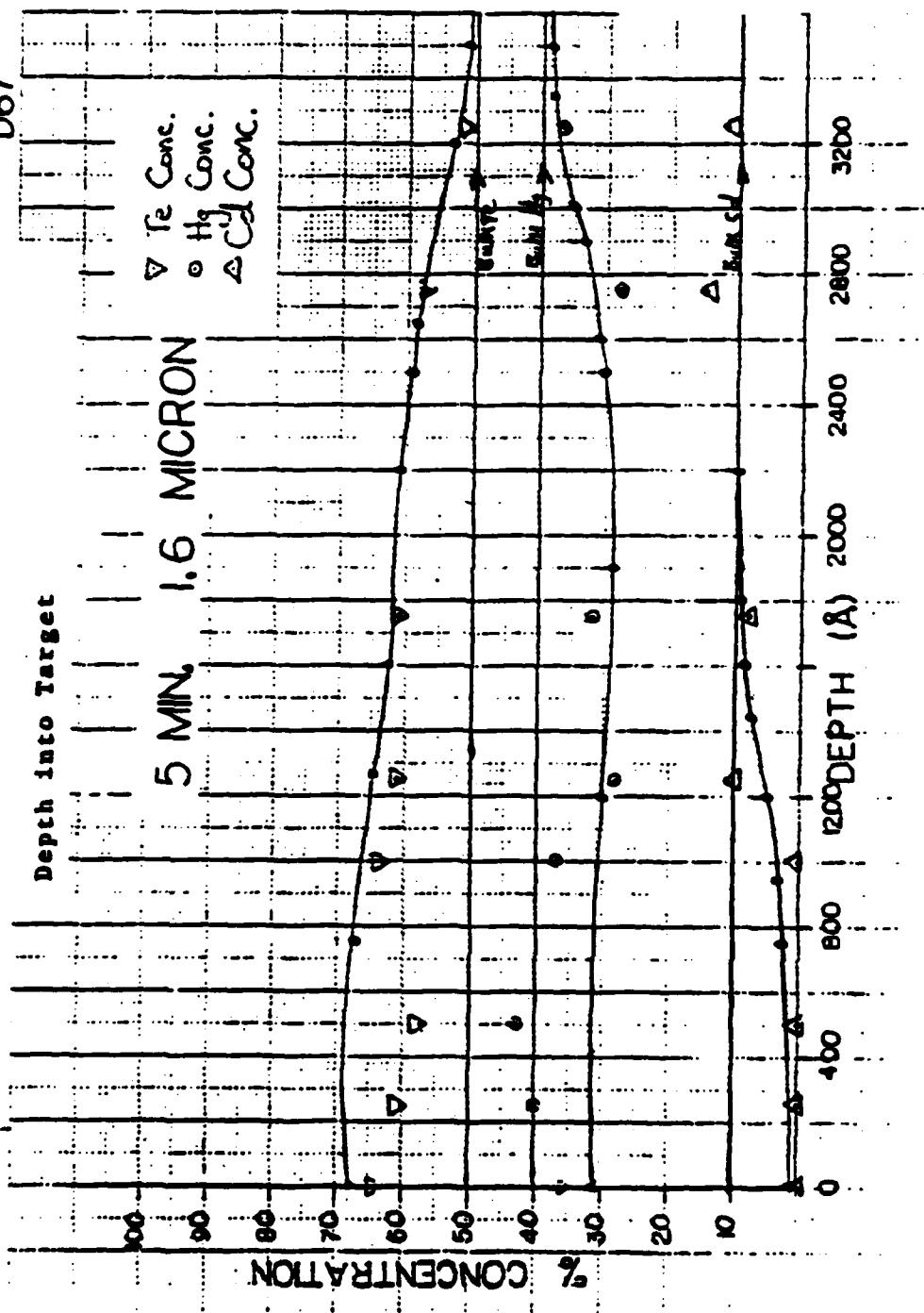


Figure 19 THE ALTERED-LAYER COMPUTER PROGRAM

```

100 REM    ALTERED-LAYER
110 REM
120 REM    AUTHOR: R. G. BOURNE
130 REM          134 FOREST AVE
140 REM          GLEN RIDGE, NJ  07028
150 REM
160 REM    A PROGRAM TO FIND HG, CD, TE CONCENTRATIONS
170 REM    AS A FUNCTION OF DEPTH INTO A SAMPLE CAUSED
180 REM    BY DIFFUSION.  THE USER INPUTS SURFACE
190 REM    CONCENTRATION, BULK CONCENTRATION, K'S AND
200 REM    THE DIFFUSION COEF'S FOR EACH ELEMENT;
210 REM    AND TIME (MIN.).
220 REM
230 REM
250 OPEN "PRINT" AS 0
260 DIM SC(3): DIM BC(3): DIM K(3): DIM CN(3): DIM D(3)
265 REM    D(X)=DIFFUSION COEF'S (A/MIN)  1,2,3  HG,CD,TE
280 LET N=1
290 DEF FNC(X)=.5*(SC(U)-BC(U))*(S1+S2)+BC(U)
300 DEF FND(X)=INT(X*10^N+.5)/(10^N)
310 DEF FNG(U)=2*SQR(D(U)*T)
320 DEF FNE(X)=(K(U)*FNG(U)+X)/FNG(U)
330 DEF FNF(X)=(K(U)*FNG(U)-X)/FNG(U)
340 DATA "Hg","Cd","Te"
345 PRINT 0: PRINT 0: PRINT 0
350 INPUT "T (min.)";T
352 LET BC(1)=40: BC(2)=10: BC(3)=50
355 FOR J=1 TO 3
360 READ A$
370 PRINT A$;" SC, K, D";
380 INPUT SC(J),K(J),D(J)
390 NEXT J
400 RESTORE
410 PRINT 0, "DEPTH", " Hg", " Cd", " Te"
420 PRINT 0, "-----", "-----", "-----", "-----"
430 FOR X=0 TO 4000 STEP 50
440 FOR U=1 TO 3
460 GOSUB 1000
470 LET CN(U)=FND(FNC(X))
480 NEXT U
490 PRINT 0, X,
495 LET CN=CN(1)+CN(2)+CN(3)
497 N=N+1
500 FOR J=1 TO 3: PRINT 0, FND(100*CN(J)/CN),: NEXT J

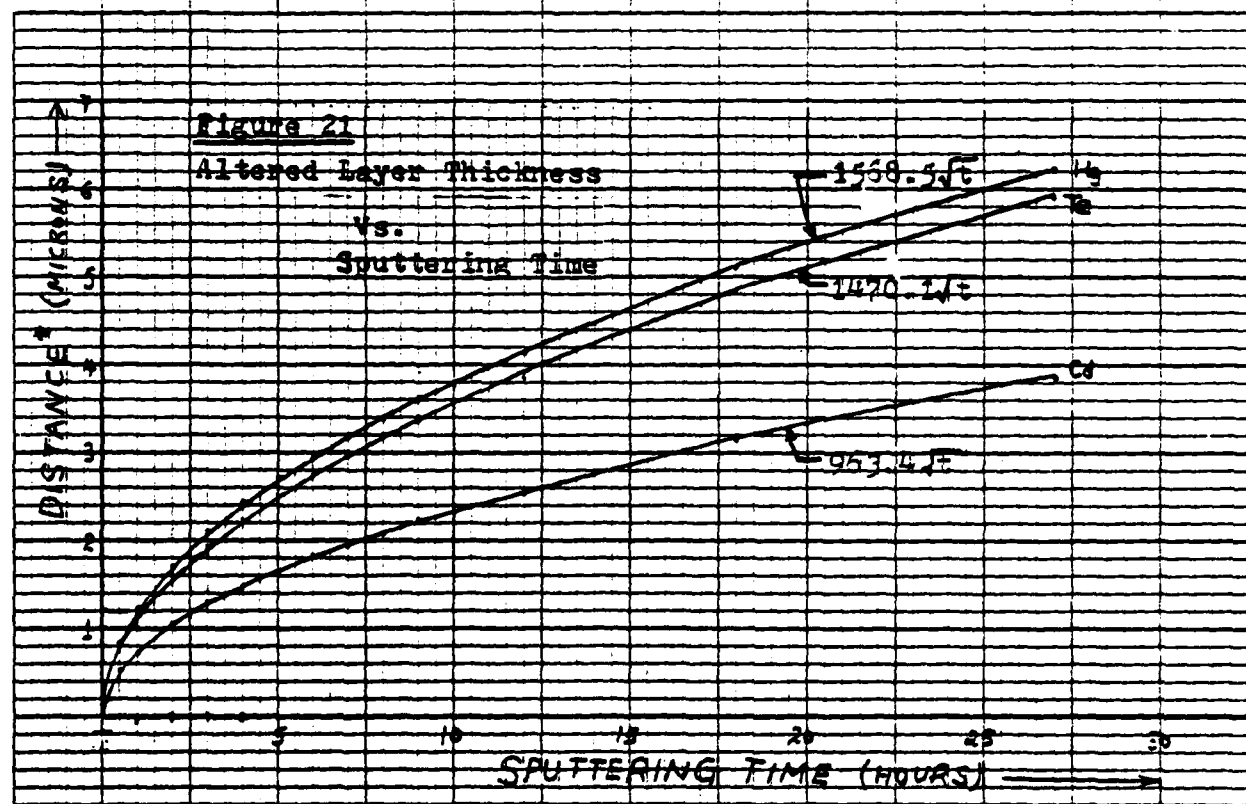
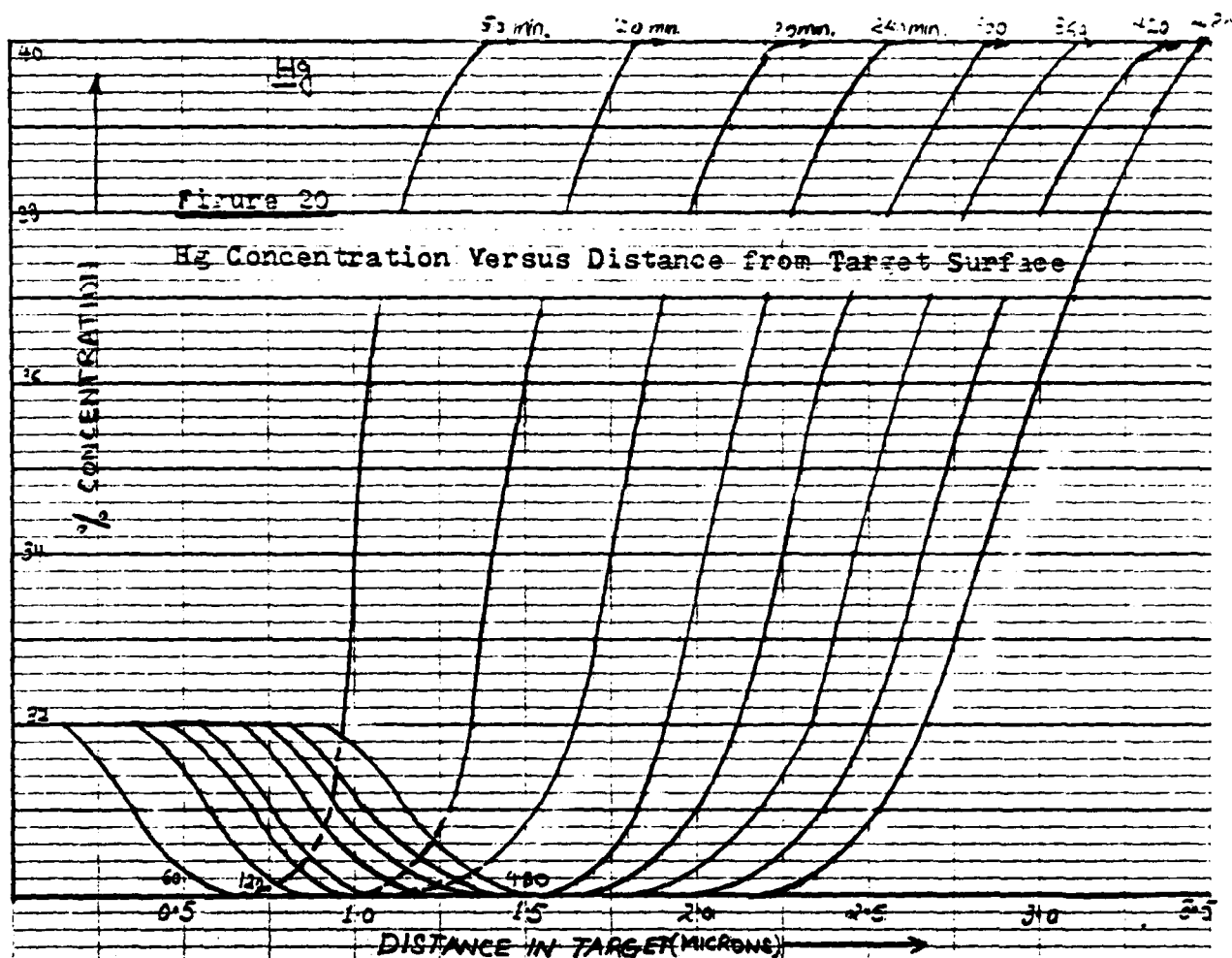
```



```

510 PRINT 0,
520 NEXT X
530 PRINT 0, "T (min.) =";T
540 FOR J=1 TO 3
550 READ A$
560 PRINT 0, "SC ";A$;" =";SC(J);"    ";
570 PRINT 0, "BC ";A$;" =";BC(J);"    ";
580 PRINT 0, "K  ";A$;" =";K(J)
590 NEXT J
600 RESTORE
610 INPUT "AGAIN (Y/N)";A$
620 IF LEFT$(A$,1)="Y" THEN 345
630 END
1000 REM  SUBROUTINE 1
1010 LET ER=FNE(X)
1020 GOSUB 1100
1030 LET S1=S
1040 LET ER=FNF(X)
1050 GOSUB 1100
1060 LET S2=S
1070 RETURN
1100 REM  SUBROUTINE 2
1110 REM  APROX INTEGRAL 0 TO ER OF  $\exp(-U^2)dU$ 
1120 LET S=0
1130 IF ER=0 THEN RETURN
1140 FOR V=0 TO ER STEP ER/100
1150 IF ABS(V)>9.2 THEN RETURN: REM   $\exp(-U^2)=0$ 
1160 S=S+ $\exp(-V*V)*ER/100$ 
1170 NEXT V
1180 RETURN

```



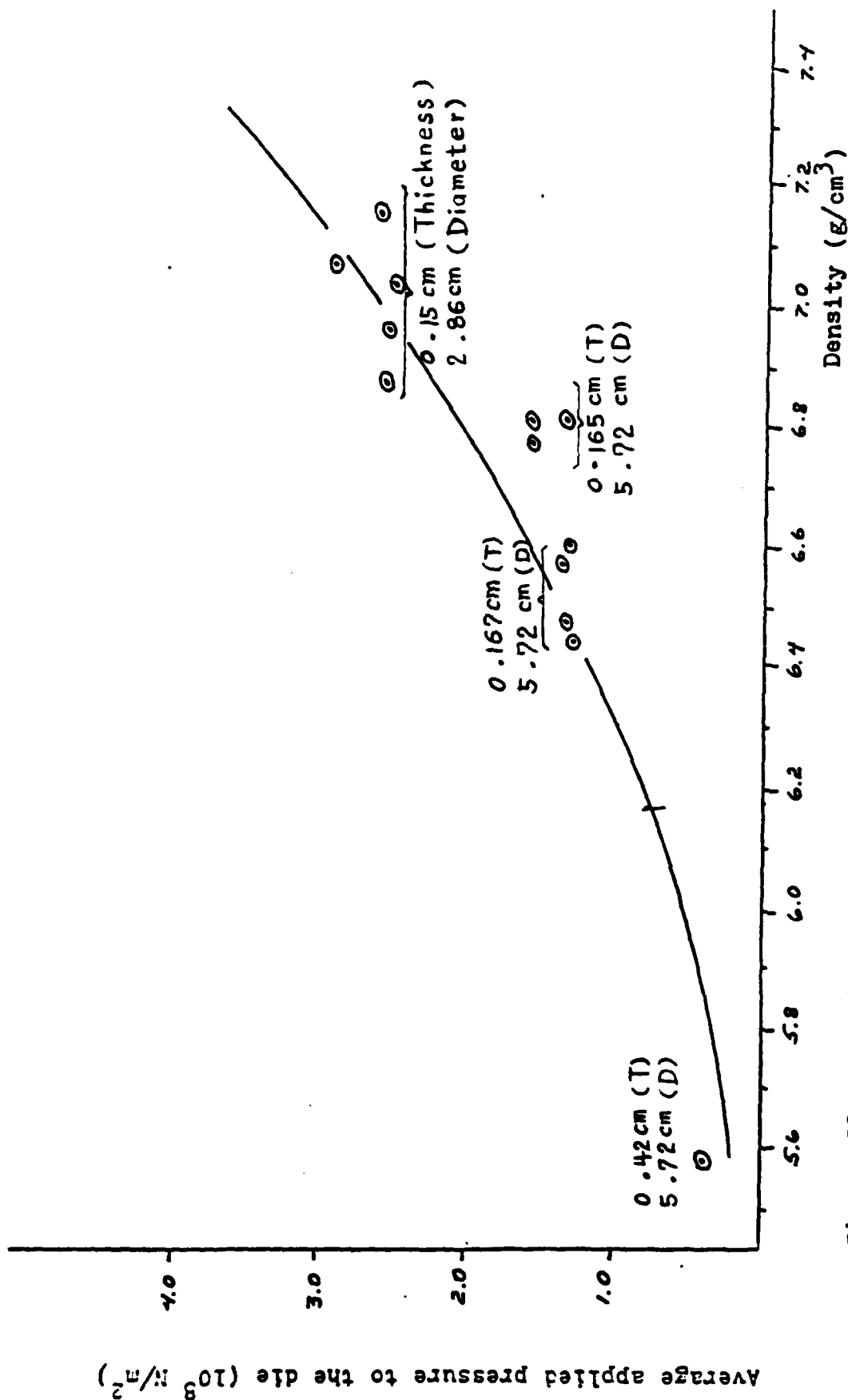


Figure 22 Density of different physical mixture ( $\text{Hg}_{0.75}\text{Cd}_{0.25}\text{Te}$  discs versus applied pressure.

**DATE  
FILMED**

**8-8**